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Orebody Complexity in Geological Control over Selective Mining

Helen Francis

A thesis submitted
to the Faculty of Graduate Studies and Research
in the Department of Mining Engineering
McGill University at Montreal

In partial fulfilment of the requirements for
the Masters of Engineering

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Abstract / Résumé

This thesis proposes a morphological complexity index for use in classifying orebodies. Formulated and tailored for application on underground steep dipping narrow base metal orebodies from Inco Limited's Manitoba Division, the complexity index was proved transferable to the base metal deposits of Inco Limited's Ontario Division. Thus it appears that the index could be applied to various styles of mineralization and orebody morphology.

The complexity classification was designed to aid in geologic control and subsequently improve mining method performance. Motivated by an industry wide move from selective mining to bulk mining, to increase productivity and improve safety. It is intended that development and application of an orebody complexity index will increase the understanding of geology and prevent the sacrifice of selectivity, minimizing dilution and ore loss. With the advent of automation, simplification in mining is necessary and thus more intelligent design and control vital. This thesis offers one means by which MDPPC (Mine Design, Planning and Production Control) could be further integrated with geological understanding to achieve such an end.

The thesis provides explanation of how such a complexity index can be used to understand mining method performance and be used for more successful mine design.

Cette thèse propose un moyen de classification des gisement minérales en utilisant un index de complexité morphologique. Cette nouvelle application a été formulée et adaptée pour les gisement de métaux de base étroit et ayant un angle de pendage prononcé de la compagnie Inco Ltée., Division Ontarienne. Ainsi, il semble que cet index pourrait être appliqué à une multitude de types de minéralisation et de morphologie.

La classification par complexité a été conçue afin d'augmenter le contrôle de la dilution et subséquemment la performance des différentes méthodes de minage. Cette thèse est grandement motivée par la transition de l'industrie minière d'une approche sélective à des types de minage en vrac afin d'augmenter la productivité et d'améliorer la sécurité. Le développement et l'utilisation d'un index de complexité des gisement aspire à minimiser la dilution et les pertes de minerai et améliorer la compréhension de la géologie, sans pour autant sacrifier la sélectivité. Avec l'évolution de l'automatisation, la simplification des méthodes de minage devient essentiel. Incidemment, un design et un contrôle plus adapté est vital. Cette thèse propose un des moyens par lequel MDPPC (*Mine Design, Planning and Production Control)*, pourrait être éventuellement intégré avec une compréhension de la géologie afin de permettre le succès d'un tel concept.

Les explications concernant l'emploi d'un tel index de complexité contenues dans cette thèse peuvent être judicieusement utilisés afin de maximiser la compréhension de la performance des méthodes de minage; et conséquemment, développer un design de mine plus approprié.

Acknowledgements

I am sincerely grateful to Malcolm Scoble, Ph.D., of McGill University and Mario Paventi, Ph.D. for their insight, guidance and encouragement. The provision of data and advice from Mr. Gary Sorenson and Greg Baiden, Ph.D., of Inco Limited is also greatly appreciated.

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SCOPE OF GRADUATE STUDIES

- to further my geological knowledge and increase my technical mining skills by researching a topic of practical application to the mining industry. Concurrently achieving a masters degree, gaining experience in the working environment and understanding further the operations involved in the total mining process.
- to study the impact and importance of geology within mining and extend my research into the area of " Error in ore reserve estimation and a reliability rating system", the topic of my Bachelors Degree.

RESEARCH OBJECTIVES

- to formulate an index to reliably quantify orebody complexity.
- to evaluate complexity within base metal orebodies in the Manitoba Division of Inco Limited. The quantification of orebody complexity is motivated by the need to maximize geological control. This is particularly relevant to Manitoba Division mines where the late 1980's saw a move away from selective Cut and Fill methods to the less controlled mining methods of Vertical Retreat, Slot and Slash Mining. This was prompted by the need for increased productivity and improvements in safety. The consequence, however, has been the sacrifice of selectivity, with an unanticipated and significant increase in dilution and ore loss. The need now exists to improve the quality of the mining process. The change to bulk mining industry-wide was inevitable and with the advent of automation it will be maintained. The need to be more intelligent in our approach to design and control, is clearly evident. The introduction of a measure of orebody complexity should be able to relate geology to mining method performance. This study aims to evaluate how its integration into the mine design process might improve mining system performance.

CHAPTER 1 - INTRODUCTION

"Mistakes don't come from what you don't know, they come from what you know that ain't so." - Josh Billings, from Proverbs (1874)

1.0 Introduction

In any industry, the process undertaken and methods followed require regular if not constant monitoring to ensure that they perform to required specifications and function in the most efficient manner. This is true of the Mining Industry where the quest for a means of measuring mining performance has never been so fully appreciated as at present.

The financial success of a mine is directly dependent upon its performance, which relates to the effectiveness of its mine design, planning and production control (MDPPC). A greater focus has recently been placed on the management and organisation of mining with the development of new technology and awareness of automated applications. One management rationale to exploit automation technology has been presented by Knights and Scoble (1995), termed Lean Mining (discussed further in chapter 2). This aims to enhance and accelerate cash flows over the life of a mine by focusing on reduction of: throughput times, stockpiles for volume and quality control; wastage and rework.

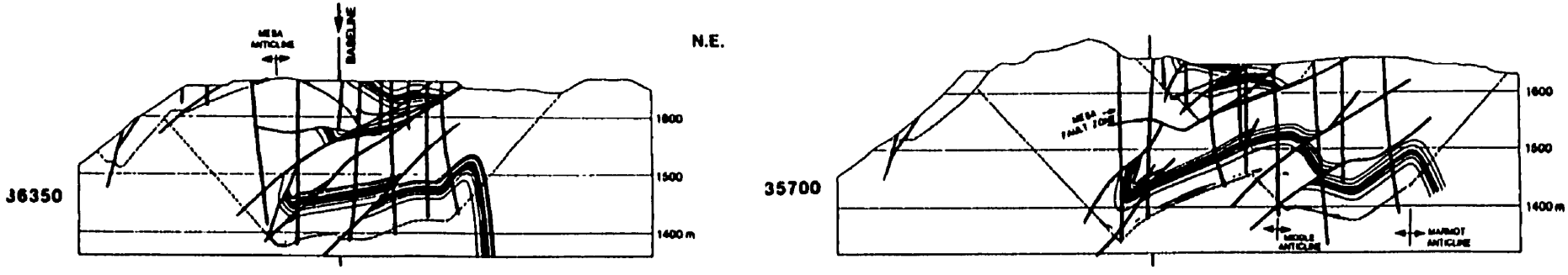
In order to facilitate the development of more efficient and effective MDPPC the opportunity exists to access, integrate and analyse new mining information technology. Intelligent design, planning and production control can be based upon access to key geological information and an understanding of the design circumstances. Intelligent mining derives from the dependence upon expertise gained from experience and analytical capability, i.e. knowing the mining circumstances and making effective and timely decisions.

Geological Control is a critical component of MDPPC. It relates to the generation of geological data from exploration and delineation activity, using various sensing sources, followed by the fusion, analysis and interpretation of this data.
Effective Geological Control aids the decision making procedures, estimation, modelling and information management relating to ore estimation, geological and geotechnical modelling within MDPPC.

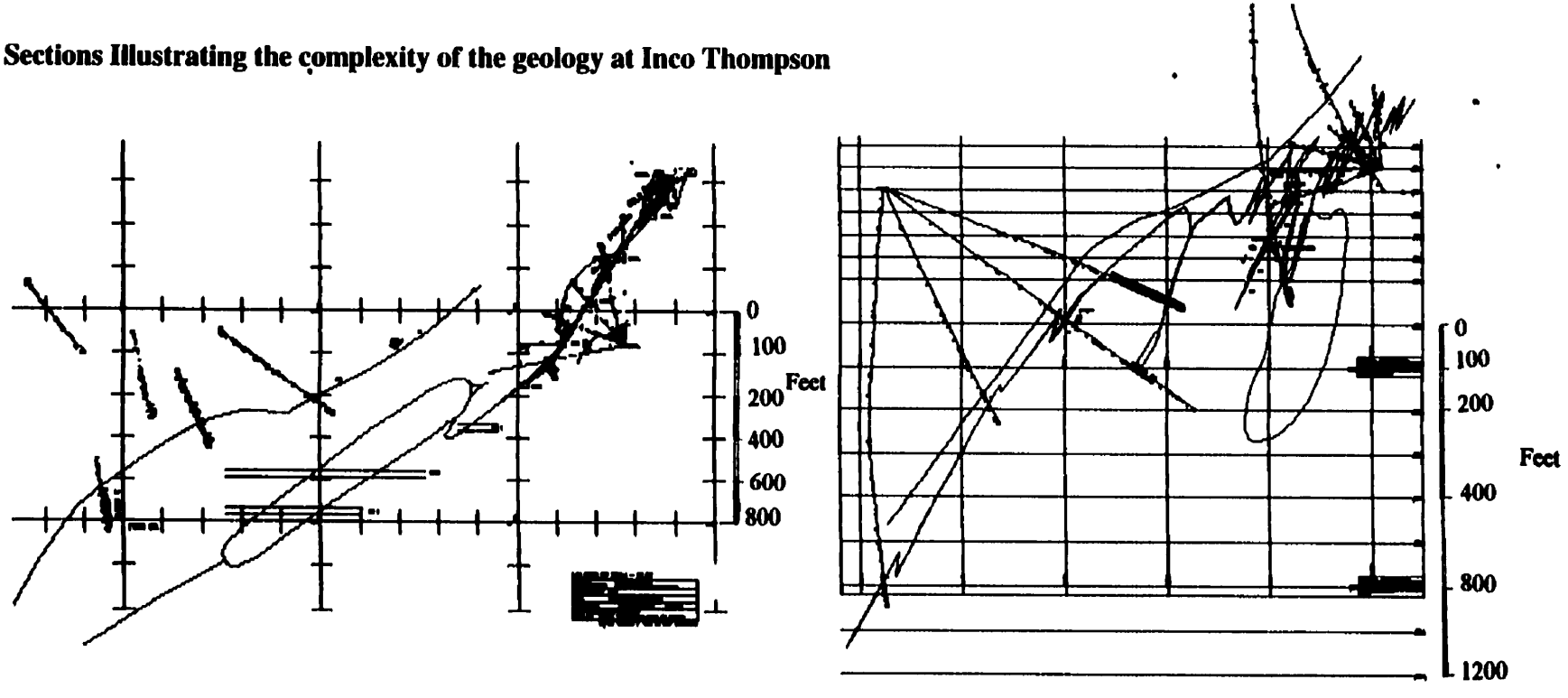
Current research within the context of Geological Control tends to be focused on the sensing issues, with a past emphasis on ore estimation for exploration and the development of geostatistical techniques for mining feasibility studies and design. **Orebody Complexity,** relates to those characteristics of an orebody that can be defined independently as parameters that influence the performance of a mining method. It exerts strong influence over the nature and effectiveness of Geological Control. Little formal work has been undertaken on the characterisation of Orebody Complexity.

Sommer (1992) observed that, "the structure of ore is so complex and randomly variable that it is difficult to foresee that accurate models will be available...*adaptive* control should have a major impact in the mineral processing industry." Figure 1.0.1 demonstrates the range of complexity that can be associated with orebodies. This is an example of where orebody complexity has had a critical influence over mining success, at the Quintette Coal Mine, British Columbia. As illustrated, the coal seams are complex, far more structurally complex than initially estimated. Mining recovery diminished as a result of often locally unknown and complex geological structures. As a result, the mining schedule was required to be more detailed in order to maintain production levels. An upside to the increased complexity was an increase in the in-situ reserves due to intense thrust fault thickening.

Figure 1.0.1 Geological Complexity encountered at the Mesa Pit and Extension of Quintette Coal Limited., (after Gormley, 1987)



Sections Illustrating the complexity of the geology at Inco Thompson



Mine optimisation became of critical importance with the recognition that the complex geological structures increased unit operating costs by 25-35%, in comparison to the simple geology initially modelled, (Scott, 1997).

Figure 1.0.2 illustrates successful geological control at Inco's Copper Cliff North Mine, based on the integration of sensing technology for orebody delineation. In this case the application of a geophysical blasthole probe allows blast designs to be adapted to a realistic ore outline such that ore loss and dilution is minimised, and thus more selective bulk mining is achieved. Blastholes are drilled according to initial mining lines, generally based on delineation drilling and sill mapping. Prior to explosives loading the geophysical probe is sent into each blasthole. It enables the logging of rock conductivity, making it possible to differentiate between ore and waste. This allows for more detailed ore location and provides an opportunity for the blastholes to be redrilled if necessary and then be loaded in such a way as to minimise dilution and ore loss more reliably.

This thesis aims to increase our understanding of the relationship between geological control and selective mining. It considers the requirements for geological control in future automated mines, focusing on the elements of orebody complexity that hinder that control. A means of quantifying orebody complexity is presented, primarily based on information collected from Inco Limited's Thompson, and Sudbury Mines. It is intended that this approach to orebody complexity quantification can be integrated into MDPPC interpretation of data and the decision making process.

1.1 Background to Thesis

The development of this thesis stems from initial work undertaken during the author's Bachelor Degree, where "Errors in Ore Reserve Evaluation and a Reliability Rating System" were discussed and presented. This work encompassed the more strategic elements of geology, at the feasibility stage of a mine's development.

Figure 1.0.2 Successful Geological Control - the integration of geological sensing

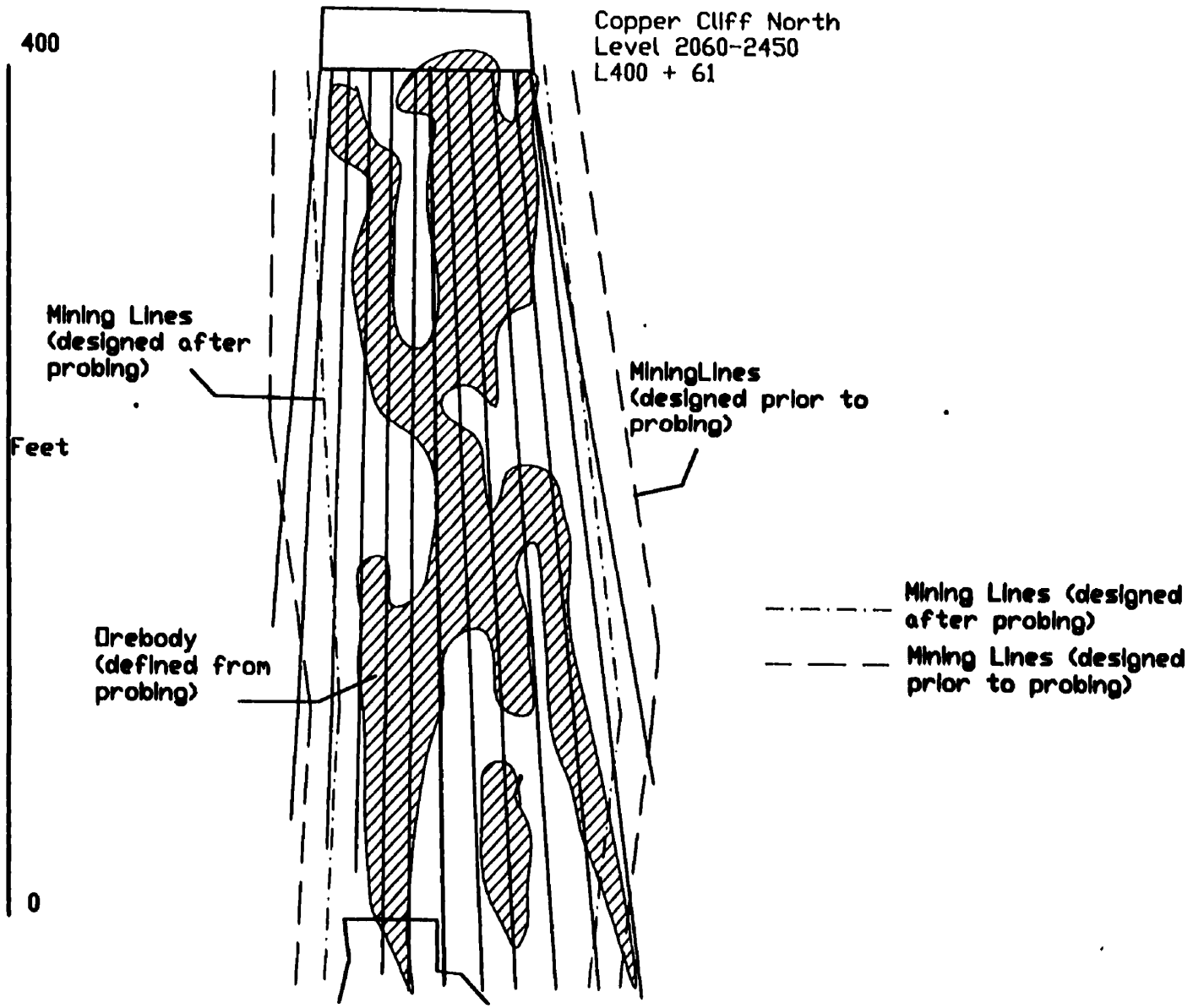


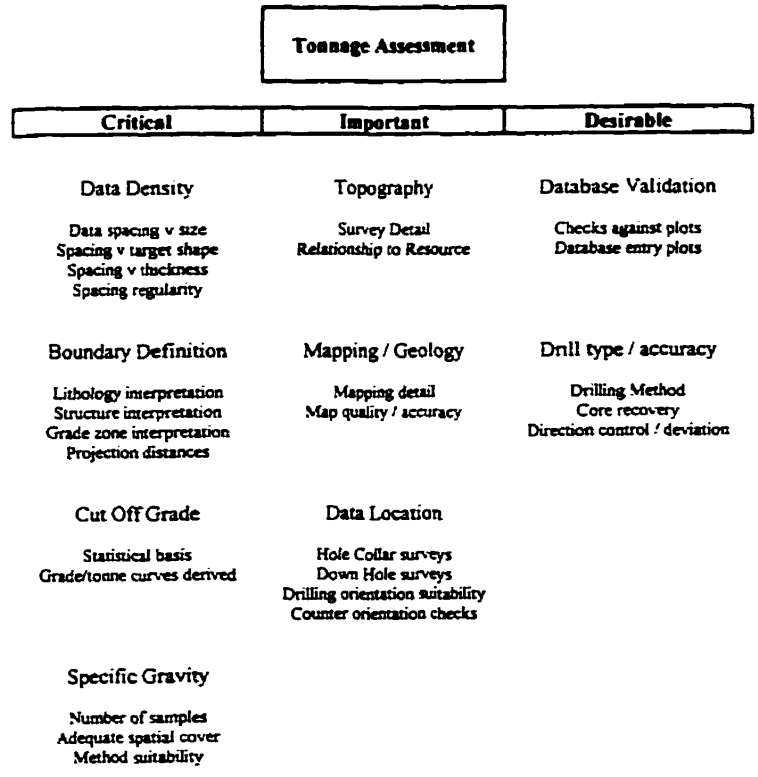
Figure 1.2.1, 1.2.2, and 1.2.3, describe in summary the main sources of error identified in the orebody evaluation process: Tonnage, Grade and Economic assessment. Within each of these categories the sources of error were determined. These were defined as critical, important and desirable, depending on the weight an error exerts on the final reliability of the evaluation. A rating system was then devised to determine low reliability elements of the orebody evaluation.

Many of the sources of error involved in the strategic planning of a mine, also recur later, once production commences. These tend to be of a more technical nature. In terms of geological control during production, the Tonnage (Figure 1.2.1) and Grade Assessment (Figure 1.2.2) sources of error tend to be more problematic to the geological control.

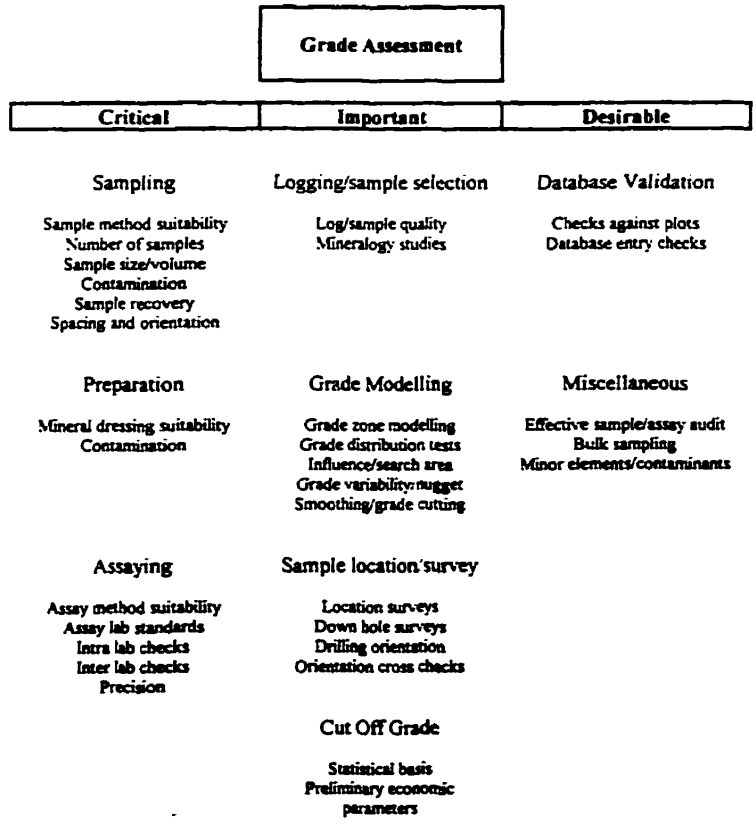
This thesis will focus on the more tactical geological control issues applying to routine mine production. The reliability of geological control related to orebody complexity, associated with boundary definition, mapping and grade modelling will be studied in particular.

The author has spent time in this study working and observing the practical application of mining geology at Inco Limited's mining operations in both Manitoba and Ontario. Based on experience and data gained from these opportunities, it is intended that this thesis will provide a concise and comprehensive insight into geological control, focusing on orebody complexity.

Figure 1.2.1 Tonnage Assessment (after Francis, 1995)



1.2.2 Grade Assessment (after Francis, 1995)



1.2.3 Economic Assessment (after Francis, 1995)

Economic Assessment

Critical	Important	Desirable
Capital Costs	Taxation and Government Policy	Database Validation
Have both fixed and working costs been defined Suitability of the capital costs evaluation technique	Adequate assessment of tax structure and its likely fluctuations	The basis for the economic assessment is from more than one source Database Entry Checks
Operating Costs	Sensitivity and Risk Analysis	
Mining and Extraction costs v recoverable value of the mineral Milling, beneficiation, processing costs v recoverable value of the mineral Smelting, refining, finishing costs v recoverable value of the mineral Transportation costs v recoverable value of the mineral Other costs v recoverable value of the mineral Recoverable value v Mining method	Suitability of the methods applied Adequate number of scenarios considered	
Metal/Mineral Price	Environmental Considerations	
Marketing Strategy Basis for Predicted National Interest Fluctuation Basis for Predicted Metal/Mineral price fluctuation	Necessary Environmental Protection Measures Costs Reviewed adequately Allowance for Environmental Remediation costs at close of operation	

CHAPTER 2 - SELECTIVE MINING

2.0 Selective Mining

The more severe competitiveness required in current and future mining requires the ability for high recovery methods to be operated that achieve sufficiently selective extraction of ore. The balance between these two objectives in the past has been handicapped by inadequate knowledge from ore delineation. Often to achieve one objective the other has to be sacrificed. For example, selective Cut and Fill methods are currently being replaced by the high productivity bulk mining methods. As Inco's, Thompson Mines, for example, experienced this change then the benefit in improved productivity was accompanied by ore dilution of 30% or more (Pers. Comm. Sorenson, 1997). This was a level beyond that estimated and incorporated into mining plans, and resulted in significant financial losses. This Chapter discusses the elements of selective mining, providing an overview of the suggested rationales by which selectivity and increased productivity can be achieved simultaneously.

2.1 What is Selectivity?

Selectivity has been defined as a measure of the recovery (relative losses) and cleanliness achieved (relative dilution) within the mining process (Knissel et al, 1995).

$$\text{Selectivity} = \text{Recovery}^{(1+w)}\,\text{Cleanliness}^{(1+w)}$$

$$= (\text{relative losses})^{(1+w)}\,(\text{relative dilution})^{(1+w)}$$

$$= (1-l)^{(1+w)}\,(1-d)^{(1+w)}$$

Where: l = Losses

d = Dilution

w = factor to weight the importance given to mining losses and dilution

$w = -1 < w < 1$

Figure 2.1.1 Selectivity (the interdependency of mining losses, dilution and recovery rates)., after Knissel et al (1995).

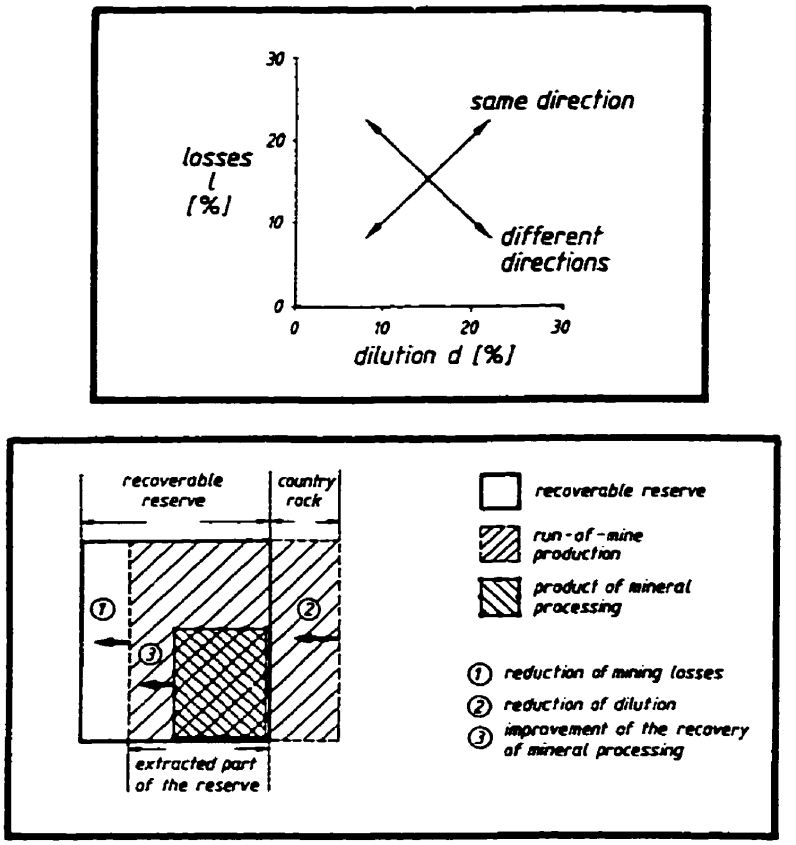


Figure 2.1.2. The economic impact of selectivity., modified from Knissel et al, 1995.

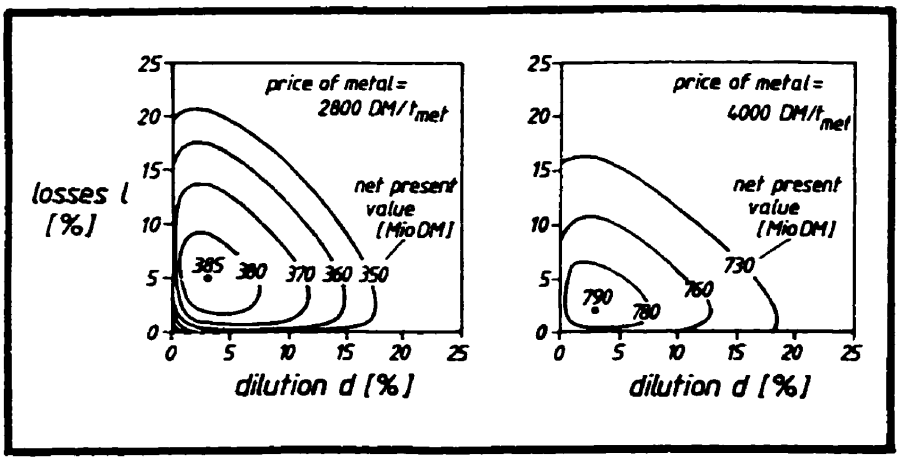


Figure 2.1.1 describes selectivity (and the interdependency of mining losses, dilution and recovery rates). A selective mining process maximises the recovery of the ore, minimizing the amount of ore loss, whilst producing the cleanest product possible by minimizing dilution. Importantly, optimum dilution does not imply minimum dilution, but a balance between the cleanliness of the operation and cleanness of the product in terms of the value of the end product. This economic impact of selectivity is highlighted in figure 2.1.2 (adapted from Knissel et al, 1995).

2.2 MDPPC effects on Selectivity

Mine design includes all aspects required for the mine to be opened, developed and operated. Mine design begins at the feasibility stage of a mine where significant signs of ore lead to the development of shaft sinking and tunnelling for exploration purposes. This continues through to layout of underground excavations for the life of the mine including development not only for ore retrieval, but safety, maintenance, supply services, power, ventilation, water control and reclamation.

Mine planning is inextricably linked to mine design, but more specifically deals with the selection of mining methods and facility requirements.

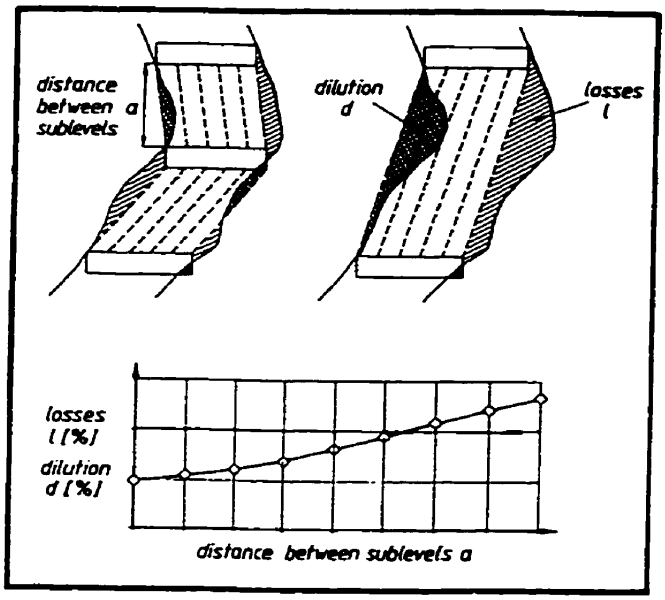
Mine production control acts as the balance between the economic climate, and the designed requirements for production rate and quantity from the mine to the mill. Concerned not only with quantity of ore but quality, control is required in order to achieve a profitable and efficient mine. This ensures that the mill receives and expects ore of a particular grade, quantity and mineralogy. Control is also extremely important in maintaining safe working conditions through adequate ground control.

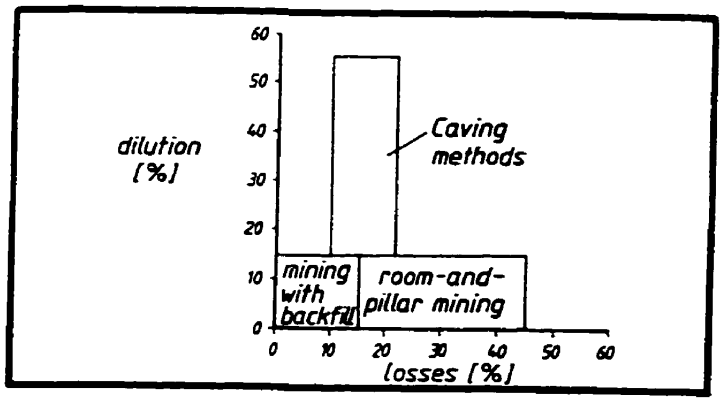
Mine design, planning and production control can have a significant effect on the selectivity of a mining operation, affecting dilution and losses. Knissel et al (1995), identified that different mine layouts and mine technology influence mining losses and dilution with opposite effects. For example, a faster extraction rate in a caving operation may reduce the losses incurred, although it is likely also to increase the amount of dilution suffered. However, changes in the mining method defined in the long term planning of an operation, for instance, the distance between sublevels and the type and quality of backfill to be used can influence the mining losses and dilution in the same sense. Figure 2.2.1 illustrates these effects (adapted from Knissel et al, 1995).

2.3 Mining rationale and Selectivity

The need for a change in mine extraction rationale has been recognised recently. As industry has recognised that more technology may increase efficiency, then it has also become aware that it will do so only with limited benefits. Improvement in the effectiveness of the processes themselves will be required (Morrison, 1995).

Figure 2.2.1 Mining Method influence of Mining Losses and Dilution (after Knissel et al, 1995)





2.3.1 Lean Mining

Lean Mining has been presented as a rationale inspired by the implementation of advanced technology in the manufacturing industry. This rationale is designed to improve the selectivity of mining operations whilst increasing production levels. In summary, (a fuller discussion of Lean Mining is presented by Baiden, 1995), the pre-requisites to achieving lean mining is the ability to make rapid decisions (agile decision making), rapid deployment of equipment (agile equipment), and selective extraction of ore. In order to achieve agility, then situation changes whether local or global must be anticipated and readily responded to. Thus economic (e.g. commodity price), social (e.g. safety) and technical (e.g. geological) changes in circumstances are significant. Agility encompasses responsiveness on the part of the mining process to permit avoidance of production difficulties once identified; lack of responsiveness may arise from limitations in the control system or the design of the machine system itself.

The ability to mine selectively is strongly dependent upon the knowledge of the orebody and its host rock, and the ability to adequately anticipate the variability of the orebody. The variability of the orebody is defined in this thesis as its complexity, which can include, for example the grade distribution, morphology and geomechanical characteristics. Variability bears significant influence on selectivity, since it strongly influences mining losses and dilution.

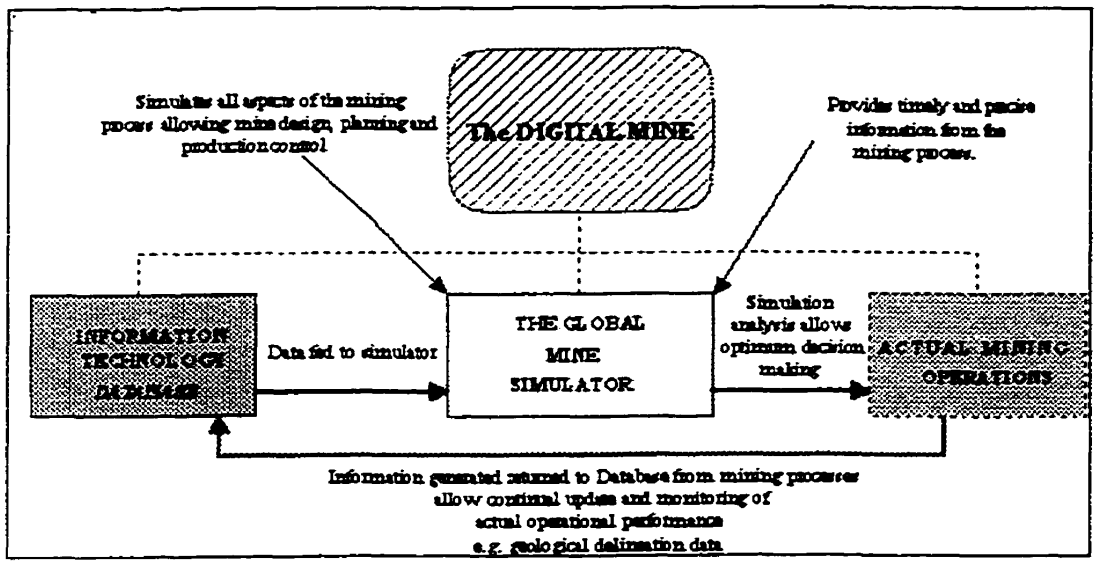
2.3.2 The Digital Mine

The rationale of Lean Mining relates to intelligent mine design, planning and production control, which is dependent upon information. The concept of a mine revolutionised by the integration of information technology is represented by the **Digital Mine** (Figure 2.3.2.1). Intelligent MDPPC requires: *access to adequate and appropriate data both historical and current; and the use of a knowledge based decision support system* where 3D visualisation, virtual reality and other artificial intelligence techniques can be integrated with CAD and simulation techniques (e.g. Automod™), and continuously updated as more data becomes available. The Digital Mine supports this requirement and should ensure that the design performance is comprehensively simulated under realistic circumstances in order to produce a final system which is highly reliable. The Digital mine would provide a mine "in which integrated information and process control systems act to reduce information delays, enhance decision making and improve the responsiveness of mining operations." (Knights and Scoble, 1995). The ultimate outcome of the Digital Mine concept is that mine design should aim to approach the situation where the engineer and geologist can monitor the performance of a particular mine plan option in excavating a selected orebody model through animated simulation. This should allow scenarios to be compared and the most efficient and productive mine design option to be chosen, i.e. the design which is the most efficient or lean. Thus in operation a mine should achieve greater selectivity, whilst maintaining a high level of productivity.

2.4 Summary

Selective mining is integral to the drive towards more efficient mining, as recognised in the new operational rationales that are evolving for the future technologically advanced mine.

Figure 2.3.2.1 The Digital Mine Concept



The influence that selectivity exerts over mining performance cannot be ignored or sacrificed for productivity gains. Although it is recognised that the future, more automated mines will likely perpetuate bulk, highly productive mining, the new rationales and integration of information technology should facilitate more effective geological control such that selectivity can be prioritised. The more specific issues of geological control will be discussed further in Chapter 3.

CHAPTER 3 - GEOLOGICAL CONTROL

"The public, lacking in experience, is often wont to exaggerate the conclusiveness of drilling."- Arnold Hoffman, Free Gold, 1947

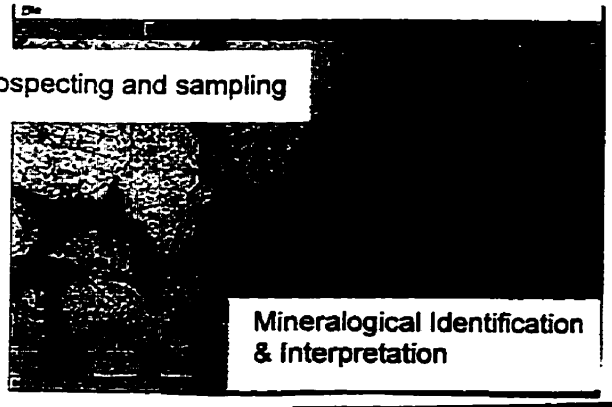
3.0 Geological Control

The broadest perspective of geological control in a strategic sense starts at the very beginning of a mine's life, the exploration stage. It then continues through until mine closure. Throughout the mine life geology plays a critical role in the short and long term decision-making. Figure 3.0.1 illustrates the geologist's role from the exploration and delineation phases through to production. This chapter attempts to characterise geological control from the mine geologists viewpoint, focusing particularly on how it relates the MDPPC and technology development.

3.1 Mining Geology

The mine geologist is responsible for providing restraining or directing influence over mine design, planning and production, based on geological knowledge, experience and understanding of the environment. Control of the mining system is based on the geological acquired knowledge. The mine geologist is responsible for collecting and managing geological data as well as its interpretation and reserve estimation, being involved in MDPPC both indirectly and directly. Often based on limited exploration and further delineation drilling information, together with a certain amount of surface and underground mapping, the geologist is responsible for determining the orebody location, geometry, orientation, mineralogy, grade, distribution and tonnage. A constant concern is the quality of the geological information involved and reliability of its interpretation.

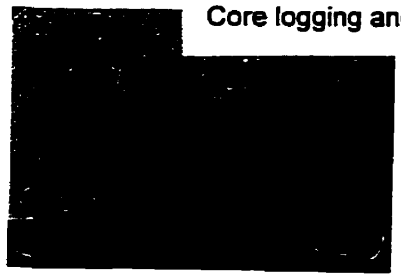
Figure 3.0.1 Diagrammatic representation of a geologists role from exploration to production.

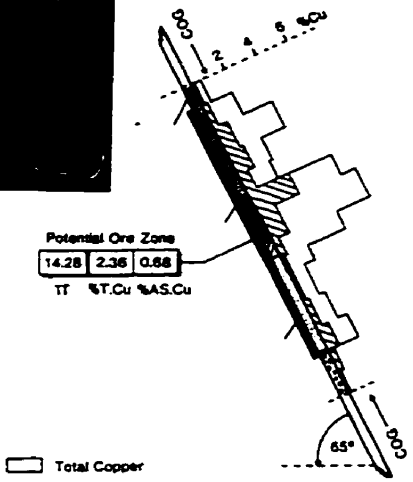


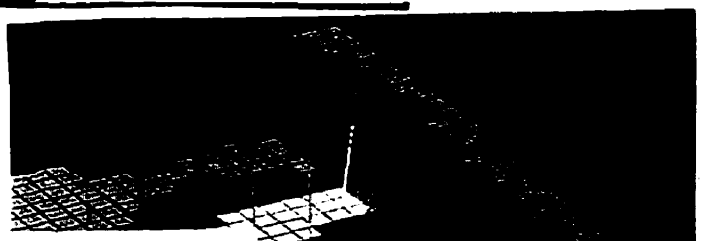
Prospecting and sampling

Mineralogical Identification & Interpretation

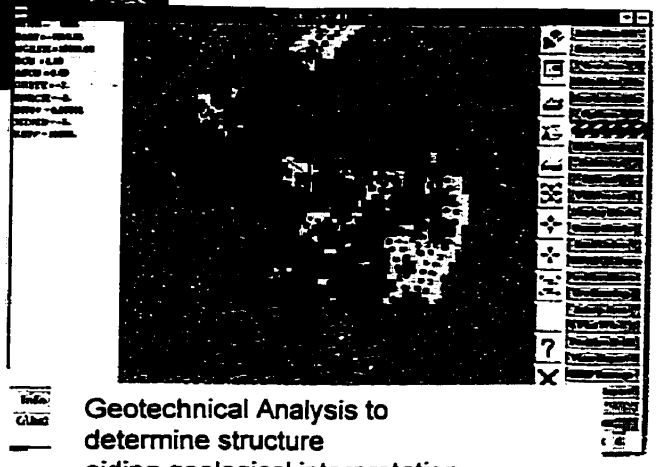
Exploration and delineation drill hole
Core logging and assaying





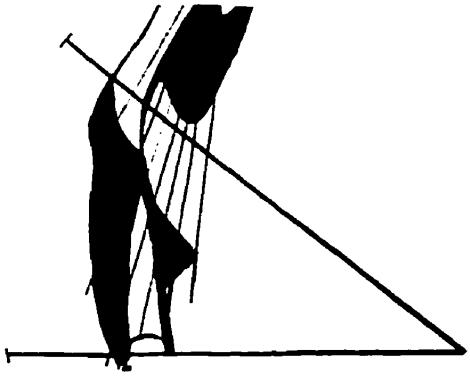


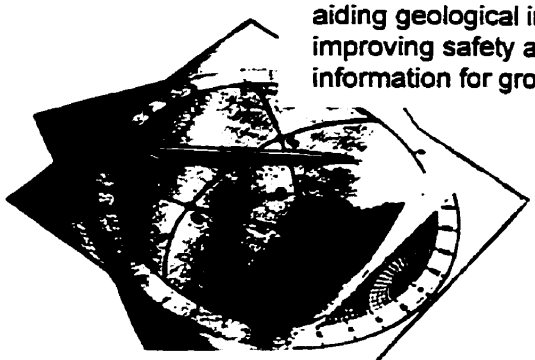
Orebody Modelling
Geostatistical Grade Distribution
Geological Interpretation
Cut-Off Grade Modelling



Design of stope layout
Continued delineation prior to stope blasting

Geotechnical Analysis to determine structure aiding geological interpretation, improving safety and providing information for ground control





Geological Reconciliation of Grade and Tonnage

Muck pile and ore pass sampling to inform mill of grade they can expect

Reliability is governed by information density, quality and assaying accuracy. Geological interpretations are often very subjective depending upon experience and information availability. Figure 3.1.1 shows a geological section from Quintette Coal Limited's Mesa Open Pit, and quite clearly reveals how interpretations of geology vary. In this case the blast holes failed to reveal structural discontinuities in the coal bands resulting from thrust faulting and lead to a much simpler and inaccurate interpretation of the geology than that which geophysical logging revealed.

An interpretative problem commonly faced by underground geologists arises in stope design based on limited information from delineation drilling and sill mapping. Figure 3.1.2 shows a section from Inco Limited's Crean Hill Mine, Ontario, where initial interpretations of stope geology can be compared to information from subsequent geophysical logging of blastholes. The probe is sent down each blast hole prior to explosives loading and is able to distinguish ore from waste, allowing some adaptation of the blast design prior to its implementation. In this case the mining lines could be re-designed such that a significant amount of ore loss and dilution was avoided. This problem encompasses the principle of reconciliation in ore production, which is an area of growing concern for the mine geologist (discussed further in Chapter 5).

In all cases the overall objective for the mine geologist is; to aid the engineers and management, through understanding and knowledge of the environment, such that:

- recovery is maximised
- dilution is minimised
- whilst productivity and safety is maximised

Figure 3.1.1 Geological Complexity at Quintette Coal Limited's Mesa Open Pit- interpretations vary, (modified from Gormley, 1987).

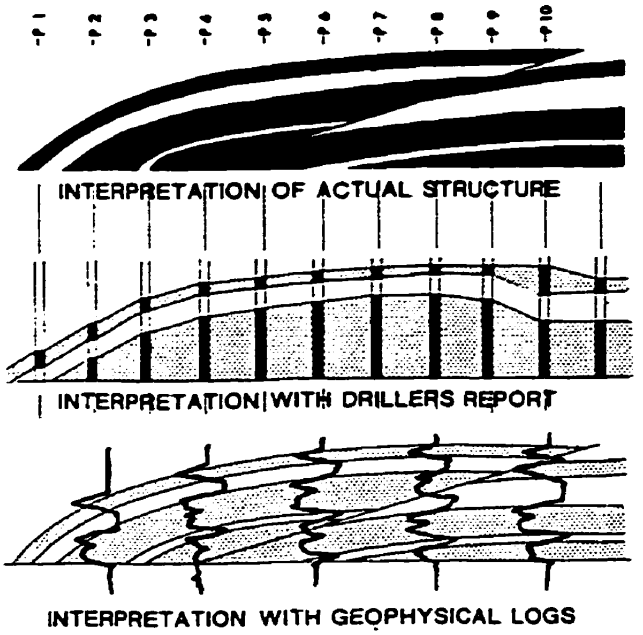
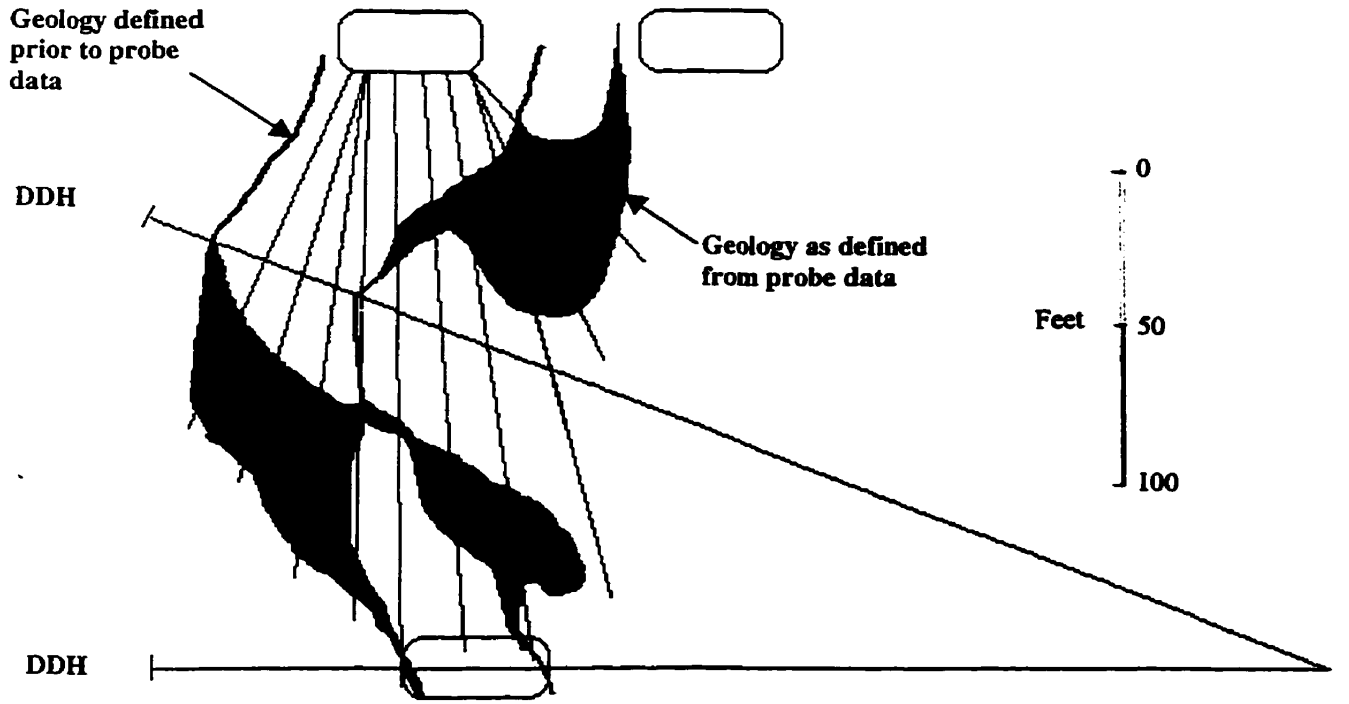


Figure 3.1.2 Probing at Crean Hill Mine, illustrates the differences between delineation information and blasthole probing



3.2 Geological Control and MDPPC

Geological Control affects the quality of the mine design, planning and production control decision making and the subsequent agility of the mining process. An inherent lack of agility in the mining process will occur if mine development layouts are inadequate, such that they do not suit the actual geological conditions finally encountered. That is, commitments to underground development layout, sublevel interval, stoping sequence, etc. affect flexibility and the ability to adapt to geological variability.

An example of the importance of agility can be seen if we consider a VRM stoping situation as described in 3.2.1 and 3.2.2. With an agile system, once the blasthole probe logging has provided the on-line update of geology, then the mining system would be able to adapt and achieve the more selective method shown in figure 3.2.2. In this case, diamond drilling initially provided two sections through the ore zone. Additional orebody information, however, was generated by using a geophysical borehole logging tool (similar to the example provided in figure 3.1.2), after the boreholes had been prepared. This probe was able to discriminate between barren waste rock and sulphide mineralization, and each ITH blasthole was logged based on this approach. Thus the ore delineated by the two initial diamond drill holes is in clear disagreement with that defined from this subsequent logging. This demonstrates the hazards of unplanned dilution and low recovery when geological control is inadequate. Figure 3.2.2 demonstrates that, with agile decision-making support, the mining process is responsive to new information, and selective, by avoiding unplanned dilution and recovering additional ore.

It has been calculated for Inco's Ontario Division for 1995-1996 that the value added due to the utilisation of such a probe was $30.0 M in annual savings. With almost 200-250 stopes being probed prior to blasting, $5.0 M was saved as a result of not blasting and mucking waste rock, whilst $25.0 M was gained through extracting additional ore as indicated by the probe. (Pers. Comm. Thompson, 1997).

Figure 3.2.1
Delineation Information based geological interpretation & subsequent mining lines

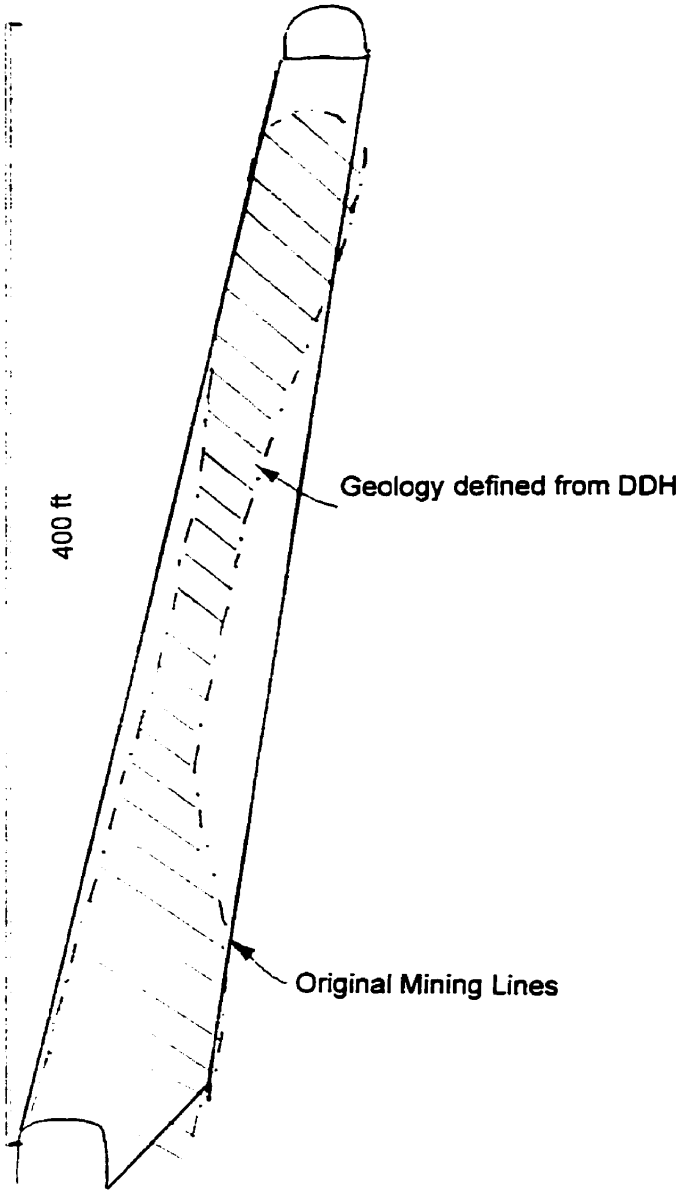
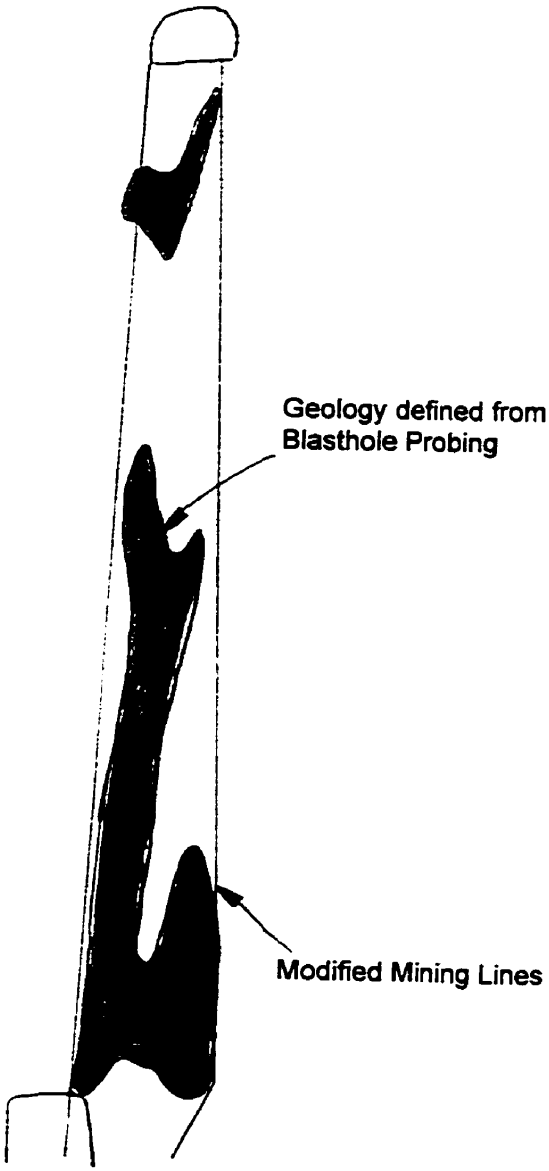


Figure 3.2.2
Probing information reveals greater detail of information thus an agile system allows the selectivity of the mining system to be improved



The sections are adapted from those collected from Copper Cliff North Mine, Sudbury.

Figure 3.2.3 graphically displays the increase in number of stopes probed each year since 1991, whilst Figure 3.2.4 and Plate 3.2.5, presents pictorially the Inco -1 Probe.

A similar problem in open stoping is faced at the Birchtree Mine in Thompson, Manitoba, where serpentinised Ultramafics (SUM Units) in particular cause stope stability concerns in terms of safety, cost of support and dilution. The cost of dilution has been estimated at $22 per ton, related to the mucking, hoisting and milling of the additional waste, (Ashcroft, 1991; Paventi et al, 1992). In order to improve selectivity, research is progressing on blast design, geomechanics, numerical modelling and ground support, such that excavation design criteria can be developed which will take into account sequencing, geometry, blasting and support parameters.

Stability of long ore passes at depth is a geological control problem prevalent in the Canadian hardrock industry. A dependence upon frequently unstable passes as the main artery for ore handling makes for very inflexible mining systems. At Inco Limited, Sudbury mines, it is not uncommon for 2.4 metres (8 feet) diameter ore passes to enlarge to 4.8 metres (16 feet) diameter over time, with a proportional increase in dilution. Keeping an orepass always full in order to maintain stability though results in inefficiency.

This thesis focuses on cyclical open stoping but an example of agility problems in a continuous mining process would be one of the earliest attempts to automate an underground coal face system: the National Coal Board's (NCB) ROLF (Remotely Operated Longwall face) project in the 60's. This represented remote control on the local scale of a longwall system, i.e. powered supports and coal winning. It failed primarily because of ROLF's inability to deal with variable geology, mainly in the form of faulting. Complex geology in the form of poorly understood structure proved too convoluted to predict with any accuracy. Thus ROLF was used without any selectivity, and a high percentage of coal was both lost and diluted.

Figure 3.2.3 Illustrates the number of stopes probed each year since 1991 (Pers. Comm. Thompson, 1997)

Figure 3.2.4 The Inco 1 Probe

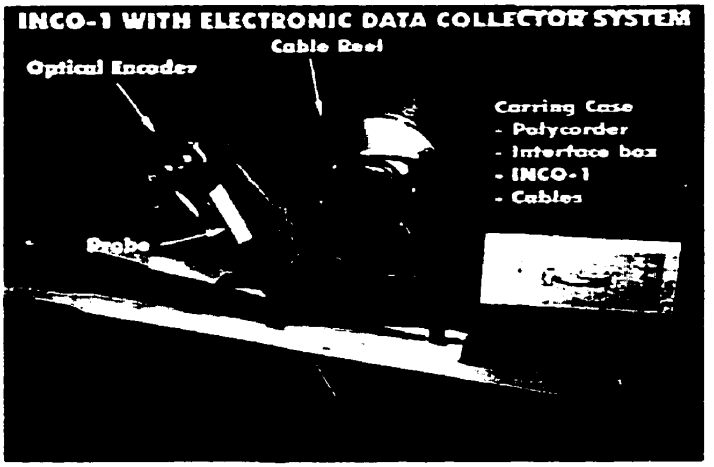
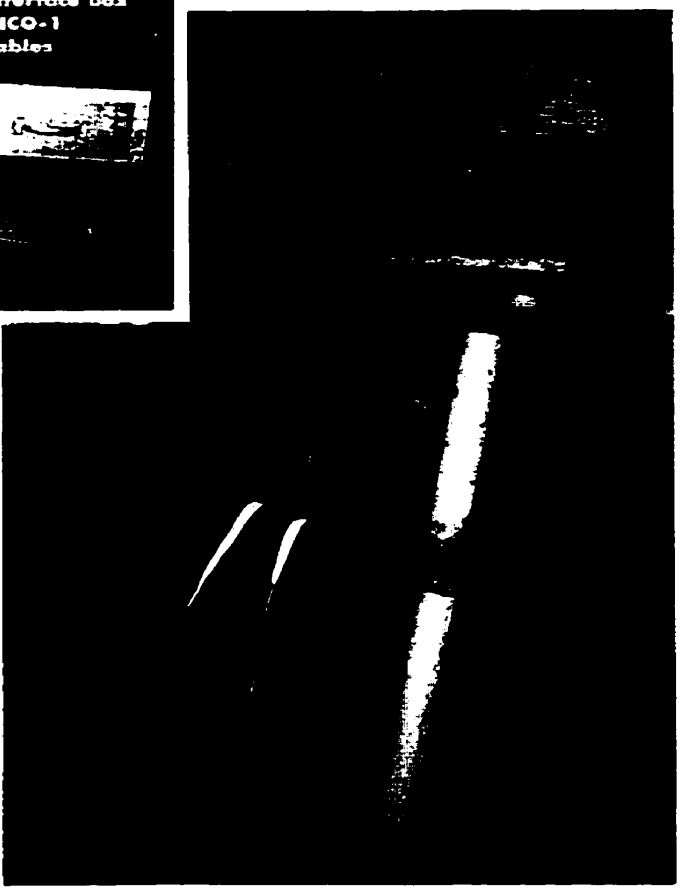


Plate 3.2.5 The Inco probe as used at Inco Thompson



Following this setback, the NCB turned its R&D focus to mechanical -electrical design of face machinery itself, as well as investing heavily in developing mine communications and machine and environmental monitoring technology (Hartley, 1980). This was aimed to realise the more immediate benefit to be gained from mine environmental and production information systems, which were able to exploit the very capital intensive, face mechanisation program underway. Subsequent NCB research has focused on geological sensing for in-seam steering (to minimise dilution) and for exploration ahead of the face by guided drilling and seismic fault detection. These projects all relate to gaining agility and selectivity in the mining process, through improved geological control.

The USBM's more recent coal mine automation strategy has so far avoided radically new machines and methods. This deliberately conservative approach sees continuous mining machines, roof bolting machines, and continuous haulage and mine ventilation systems transformed into computer assisted, remote supervised machines, operating in well understood situations.

3.3. Information Technology and Geological Control

Geological Control is dependent upon the availability of correct and timely information. However, key geological information often cannot easily be accessed and delays often occur because of the inability to "get the right information to the right people at the right time," (Martin, 1990).

Thus the decision making process is affected because the knowledge based support systems are not as efficient and data is not timely. This state has been recognised and it is commonly felt that the new information age may supply the much needed cure. Many information tools (refer to 3.4) now exist or are being developed to improve the quality, quantity and timeliness of information required by the geologist.

The need for intelligent design is the key strength of the digital mine concept, "the digital mine is one in which integrated mining information and process control systems act to reduce information delays, enhance decision making and improve the responsiveness of mining operations," (Knights and Scoble, 1995). The ultimate outcome of the Digital Mine concept (Figure 2.3.2.1) is that mine design should aim to approach the situation where the engineer and geologist can monitor the performance of a particular mine plan option in excavating a selected orebody model through animated simulation. This should allow operational scenarios to be compared and the most efficient and productive mine design to be chosen.

An example of present problems with respect to the accessibility of geological data is the recording of field generated data. "Paper forms are the typical medium used to record field-generated data," (McCullouch and Gunn, 1993) but it is a time consuming job to analyse the data and undertake all the further paperwork that goes with it, and often errors are incurred with no means of assessing how or where. In the construction field it has been surveyed that time-keeping functions required 10-15% and material management functions 26-37% of the field supervisor's time, which means that these two paper keeping processes require 36% to over 50% of their time (McCullouch and Gunn, 1993). It is evident therefore that data delays are abundant.

A possible means to reduce geological paperwork has been provided with the introduction of data acquisition with pen-based computers. A portable pen-based computer system eliminates the duplication of forms by allowing quick and easy downloading onto the main computer system.

It provides additional on-site computer support and offers the capability to retrieve and use data from databases stored in the machines memory, improving the accuracy of the data.

Thus for underground geological mapping data can be added and updated in the main computer system for the mine almost on-line (as it acquired) and thus the knowledge based decision support systems can be effective. At present Pen Systems Inc. cite that Inco Limited, Falconbridge and Placer Dome have taken advantage of their pen-based computers, which are designed for exploration, surface and underground mining operations, (Pers. Comm. Pen Systems Inc., 1996). The computers have the ability of containing AutoCad™ Drawings of levels which when taken underground can be updated and annotated by geologists immediately. Immediate logging of core is possible as geologists analyse the core retrieved and chippings collected underground this information can be recorded in the pen computer for immediate down loading at surface.

In the digital mine, comprehensive integrated systems will link mine and orebody models with real time operational data, enhanced graphics and engineering tools, and business systems (e.g. accounting, maintenance, inventory, personnel), aimed to provide agile decision making in the pursuit for lean mining.

The fusion and interpretation of excavation mapping, surveying and traditional core drilling and assaying data would be supplemented by that from what may be termed geosensing, e.g. video image analysis, radio wave imaging, seismic reflection, ground probing radar, crosshole tomography, borehole logging (density, magnetic susceptibility, gamma, calliper dilatometer logs). Production blastholes should also provide data to maintain these models by facilitating geophysical logging, surveying, chippings analysis, and ground characterisation from pattern recognition of drilling performance parameters, i.e. Monitoring-While-Drilling (Peck et al, 1989). Analysis of the models by geostatistics or other techniques provides the ability to define the ore reserve, and estimate the cut-off grade and the reserve tonnage and grade. In this manner then the digital mine would strongly facilitate geological control, which in turn will allow for intelligent MDPPC under the rationale of lean mining.

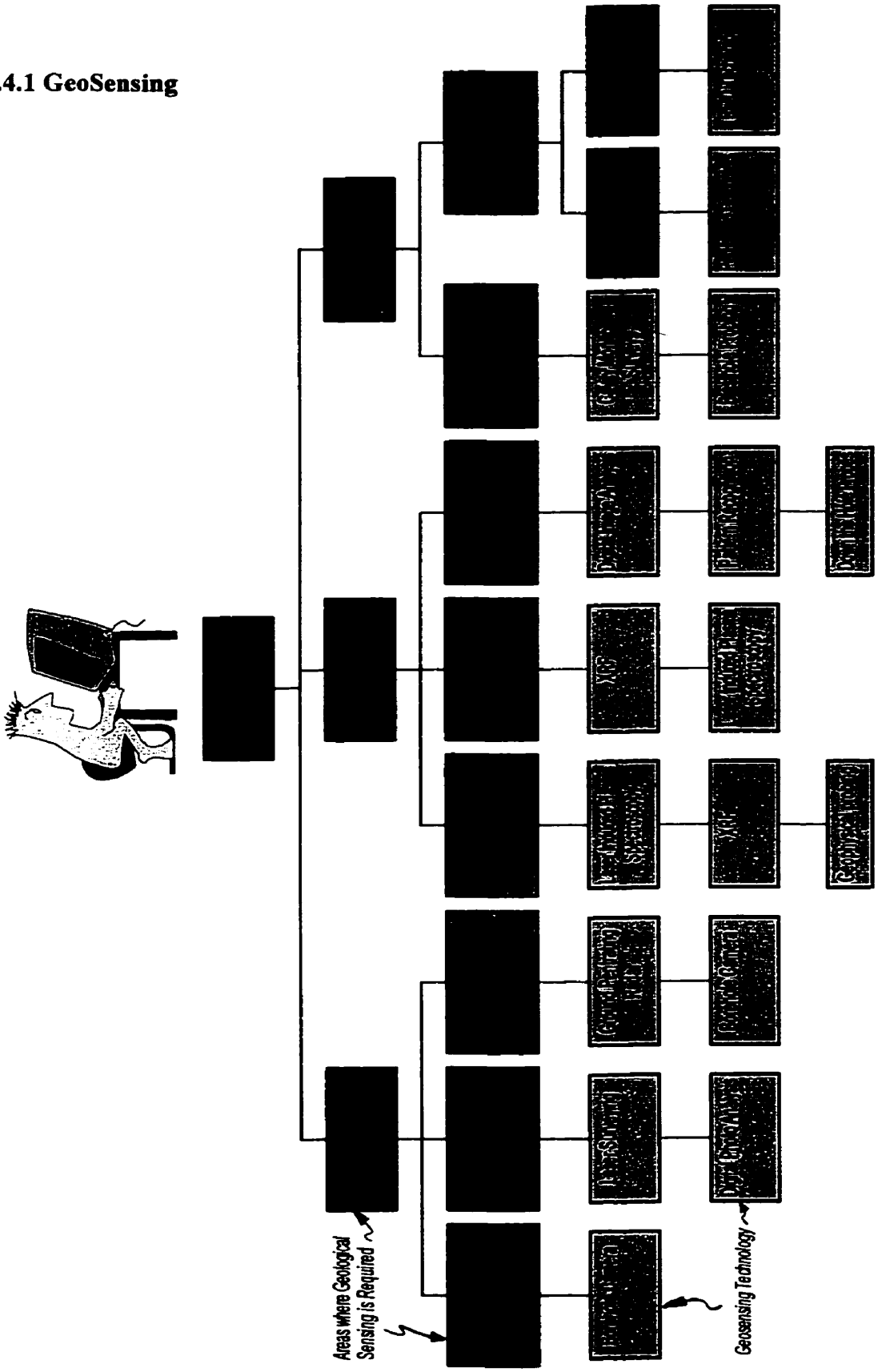
3.4 GeoSensing

Figure 3.4.1 describes the elements required in geological control and the geosensing tools that are available or currently being developed to support these elements.

Geological control will be dependent upon the development of sensors for minewide stationary monitoring systems and mobile machine systems. The following summarises initial thinking on the classes of sensors for development:

- mobile and stationary machine systems in the various mining processes; e.g. Caterpillar's 5130 and 5230 Hydraulic Excavators incorporate a Vital Information Management System (VIMS), which is an electronic monitoring system, providing diagnostic, prognostic and production information. This information can be viewed with an onboard monitor, down-loaded to a personal computer or sent off board by radio telemetry.
- mine climatic and environmental conditions;
- work force status and safety;
- materials handling and rock fragmentation;
- and ground characteristics and response to mining.

Figure 3.4.1 GeoSensing



Priority development for geological sensing would include the following:

- shape and integrity of all excavations, regardless of accessibility; requiring remote surveying in poorly accessible cavities such as stopes and ore passes. Significant progress has recently been made with the development of laser survey techniques for bench face and underground cavities. "A first-generation piece of equipment that uses laser beams and ultrasound waves combined with computer interfaces and appropriate software is being commercialised, that permits the cavity being studied and its position relative to the pit and the tunnels to be viewed on a monitor screen." (G. Sommer, 1992).

- an important feature of production control is the reconciliation of the planned and actual volumes of stope, ore pass and silo cavities and any contained fragmentation or backfill. Noranda Technology Centre and INCO-Thompson are developing an instrument to measure volume and orientation of underground cavities called the borehole laser camera. The instrument operates using a bi-directional rotating head with an infrared laser that is reflected by the rock wall and picked up by a second receptor lens. Providing constant speed of light the volume of the cavity can be measured to high precision, in only a few minutes. The advantage of this method is that unlike the Cavity Monitoring System (CMS), it can measure inaccessible cavities (Jacob and Gendron, 1994). This instrument can be used for quality control in measuring dilution while preventing and correcting it in real time. This system is planned to be integrated with a navigation system (using inclinometers and a Gyroscope) to provide information on the deviation of boreholes. The CMS tool has been used to great success at Thompson where the information gained has been used as a means to measure mining performance. This topic shall be discussed in further detail in Chapter 6.

- related to cavity volume above, it is also important to develop the means to map the exposed cavity morphology and rock units, possibly by a combination of laser profiling and digital photo-analysis.

Sommer commented in the 1992 IFAC report that "in the field of instrumentation, studies show the possibility of detecting loose rocks using infrared vision, while recently a sonic probe has been put on the market for the same purpose." The geometry of the cavity can then be related to the structural geology, mining-induced damage and ground instability in order to assess the quality of the stoping-backfilling process.

- tonnage, grade and throughput time of broken muck resident in stopes, drawpoints, orepasses, bins, vehicle buckets and bodies. An automated ore tonnage monitoring system based upon RFID technology is under development at CANMET's Val d'Or Mine (Knights, 1995). This tracks the hauled tonnage and location of LHD's underground.

- status of the integrity and capacity of ore passes and storage. Monitoring the stability of long ore passes, particularly in deep mines, is of concern. The borehole laser as developed by INCO and Noranda mentioned previously could be applied to monitor ore pass condition by using the laser as a tool for microseismic monitoring of highly stressed ground and for laser profiling of rock capacity.

- recognition of structural geology in fragmentation and excavation faces. Digital image analysis and pattern recognition offer the potential to map structural features on faces (Maerz et al, 1990); recent interest is in evaluating the remnant structure evident in fragmentation to monitor structural control over blasting (Lizotte and Scoble, 1994).

- recognition of exposed structures controlling stability; for example, mapping macro- and micro-structures in underground coal mines has proved to promote more efficient mining and roof control plans (Ledvina, 1986).

- the elusive means to recognise mineralization and measure grade on exposed faces or in fragmented rock for grade control and exploration-delineation. Progress has been made in South Africa developing a portable gold analyser (Langbridge, 1992). Whilst at Syncrude infrared oil sands grade sensing is utilised (Pers. Comm. Scoble, 1997). In salt and potash mineralization there have been successful attempts to map faces and steer machines according to recognised mineralogical features, e.g. Catalina et al, 1993, reported using vision to analyse potash ore seam structure, colour and texture.

Figure 3.4.4 Amdel on-line silica analyser

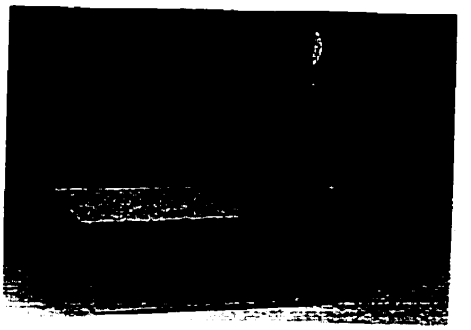
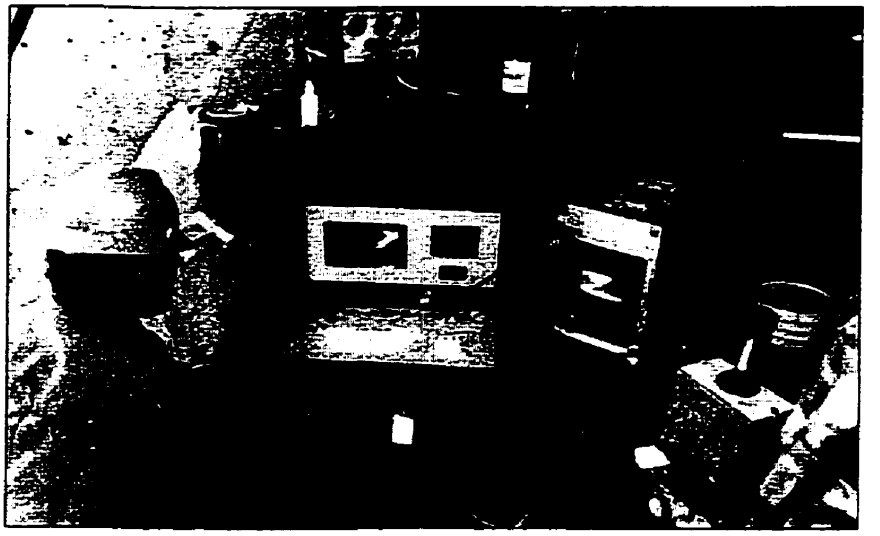


Figure 3.4.4 Borehole camera -Noranda Technology Centre



A number of separate companies and consortia (Inco, Noranda, IOC and a gold company) are working with the National Research Council for the development of a near-line mineral analysis tool, which could be placed at the collar of a drill underground or at the surface, with the ability to read chippings or core samples as they are produced. The current technology being considered for this application is Laser Induced Plasma Spectroscopy (Sabsabi, 1996), which would provide accurate spot readings of grade for any mineral of interest. The mineral analysis probe (MAP) used at Birchtree also provides spot readings of Ni grade, (Pers. Comm. Paventi, 1997).

Inco, Sudbury Division, are also researching the application of borehole geophysics for in situ down-the-hole grade, structure, lithology and rock mechanics information. Working closely with the petroleum company Schlumberger, Inco have been testing petroleum field probes for the technology transfer that may be available to mining (Pers. Comm. Cochrane, 1997).

- grade measurement in rock chippings from drilling: what in many mines is standard practice but which causes excess information delays and lack of potential agility. This is mainly as a result of the material handling time required. Technology may allow chippings to be used and handled in a far more efficient and timely manner in the future. At the IOCC Limited operations in Labrador City problems with sampling blasthole chippings arise from analysis lag time and as a result the AMDEL *on-line silica* analyser is being tested to support detailed process control that is carried out with "old" information. The information is considered old due to the fact that by the time analysis has been undertaken then it is questionable as to how representative it is of the operation currently in progress. (Goddard and Kelly, 1995). Figure 3.4.4.

- ore /waste discrimination and grade measurement in fragmentation; some initial efforts have been made to use digital analysis of images from muckpiles in stopes or drawpoints with limited success (Pers. Comm. Preston, 1997).

- measuring ore grades in boreholes: geophysical logging has proven to be successful in some instances to estimate grade, identify rock types and delineate orebody outlines; for example in Swedish mines (Wanstedt and Sundin, 1991). IOCC Ltd. is exploring down-the-hole quality probes to determine if a convenient method is available to allow for quality determinations of iron and magnetite in the field, (Goddard and Kelly, 1995).

- ground characterisation from machine performance monitoring; e.g. diggability from shovel monitoring, lithology from drill performance monitoring (Peck et al, 1989).

- rockmass structure and rock units by geophysics, e.g. Ground Penetrating Radar (GPR). Recent underground GPR surveys in the Kidd Creek Mine, Ontario, for example, were able to differentiate between andesite and massive sulphide areas, together with fault and shear zones, (Momayez et al, 1995).

- measurement of orientation of rock mass discontinuities in three dimensions, to increase the stability of mining sites and safety. The information would provide specifics on the density of support required by determining the size and shape of rock blocks which could create instability in a stope. For open pits this type of instrument would benefit ground stability by allowing tactile sensing, aiding wall design decisions when combined with a "loose detector".

- presently the Noranda Technology Centre are developing and have patented a borehole camera, which can be mounted to the head of a rotating probe. Thus the camera is able to take front and side views, and the sensor is equipped with a gravitational orientation system. The camera is also amphibious and has the advantages of producing stereonets in the field and obtaining high-quality video images of the rock masses that otherwise would be unattainable.

- minewide monitoring of the general ground response to mining will be important to develop, particularly in highly stressed rockmasses (Scoble and Moss, 1994): i.e. the ability to understand what the mining activity is propagating within the rockmass and why it is happening. This would promote more agile strategic planning and tactical control.

- In conjunction with the advantages of pen-based computers mentioned previously, an early system for direct entry of field drillhole logging was developed for a microcomputer in the Hemlo area, Ontario (Pearson et al, 1984). Mine geologists have started to use pen-based computers for direct entry of face mapping data underground. In conjunction with hand-held data recorders global positioning systems (GPS) very quickly provide surveyors and geologists with an accurate 3-D co-ordinate location. Eventually, a robotic machine for non-entry mining will be required to survey and map newly excavated faces. This will require an integrated array of sensing. A ring-laser based positioning system is being developed by Inco's Mines Research Department for the positioning of future underground mobile machines (Pers. Comm., Hinton, 1997).

3.5 Summary

Geologic Control is of fundamental importance to the successful operation of a mine. The recognised need for re-organisation and management of mines with the new rationale of lean mining, entails that geologic control becomes even more critical to agile decision making. Information technology and the concept of the digital mine, which will integrate geosensing tools with mine wide communication systems and thus the geologists', offers the means to radically improve geologic control. As agile decision making becomes a reality then the selectivity of mining should be increased whilst maintaining productivity.

Currently work has focused on the provision of information to aid geologic control, yet little formal research has considered what exactly it is that the geologist has to understand about geology in order for optimum control. The remainder of this thesis focuses on orebody complexity. In the hardrock, underground mining environment this is considered to be the most critical factor governing geological control for selective mining. It also will be a prime consideration in designing advanced technology mining systems and applying automation.

CHAPTER 4 - OREBODY COMPLEXITY

4.0 Orebody Complexity

Orebody Complexity is the basic underlying reason for the need for geological control. When orebody complexity is misinterpreted then the financial consequences can be significant.

One example of the critical nature of orebody complexity is in the development of the Louvicort Mine, (Whiteway et al, 1995). In this case, based on initial exploration and delineation drilling, proven reserves were estimated at 24 million tonnes at cut off grades of 3.89% Cu and 1.95% Zn (Anon, 1993). At this stage geologists had believed they were drilling down-plunge of the known Louvem Zones. Later drilling during underground delineation, however, has indicated complex folding. In fact subsequent to the initial estimate the tonnage was reduced by 40% to 14.4 million tonnes. The implications were significant: based on the original estimate, the company had developed a schedule and production plant to treat 4,000 tonnes per day. It was crucial that this milling rate was still met, in order to achieve the rate of return required. The mine was developed over a period of an economic recession. Consequently total costs were less than expected. The mine managed to achieve the target production levels, with only the mine life changing. As a result, the company started further exploration earlier than most mines, in order to increase their depleted reserves and extend the mine life towards the 17 years initially projected. Despite numerous examples of mines suffering similarly from difficulty in understanding orebody complexity, few have attempted to characterise it as an aid to geological control.

This chapter defines orebody complexity and discusses its components. Previous attempts to characterise and quantify orebody complexity are presented, together with earlier work by the author on orebody complexity measurement.

4.1 Definition

Orebody complexity relates to the following; the variability in the morphological, grade, geotechnical and geological characteristics of the orebody. The combined values of these characteristics control the technical and economic challenges posed by the orebody for the mining process. Collectively their impact may be termed the orebody "complexity" and represented by a complexity measure or index. The complexity index, thus relates to the difficulty in achieving a sufficiently selective yet productive and economic mining process which maximises recovery.

4.2 Elements of Complexity

The elements of complexity refer to those characteristics of the orebody that can be defined independently as parameters that influence the performance of a mining method.

4.2.1 Morphological Complexity

Morphological complexity refers to the irregularity of the external outline of the orebody. The outline may be defined in geological or economic terms, i.e. by geological contact or cut off grade. The mining method can accentuate dilution in complex orebody morphology. Should a bulk mining method be applied to an irregular and contorted orebody greater dilution will be achieved than if a selective cut and fill method had been chosen. Irregularity and ore width can affect the planned dilution in one of two ways: (1) where the orebody is narrower than the minimum mining width, the dilution contributed by the irregularity is not significant, because the mining lines will incorporate waste beyond the ore/waste contact; (2) for those orebodies that are as wide or wider than the minimum mining width, then the percent dilution contributed by the complexity of the orebody can be significant. However with unplanned dilution, either scenario could produce the same amount depending on the rock quality and morphology. Irregular orebodies are difficult to delineate and mine, particularly if steeply dipping, as is the case in most Canadian metal mines.

Generally, at widths less than 5m (with current drill accuracies), wall rock dilution due to drillhole deviation and blasting becomes too great to use open stoping efficiently, (Potvin et al., 1988).

Figure 4.2.1.1 Complexity in section and in plan - 3D (modified from Paventi, 1995)

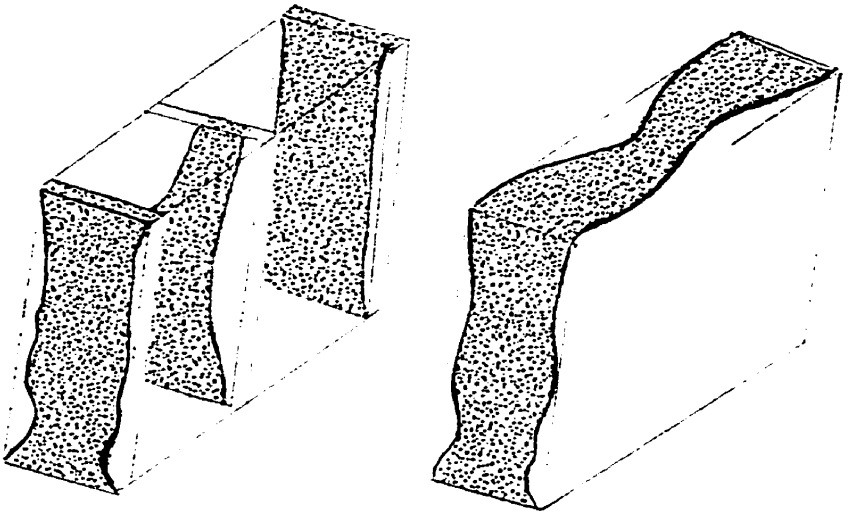
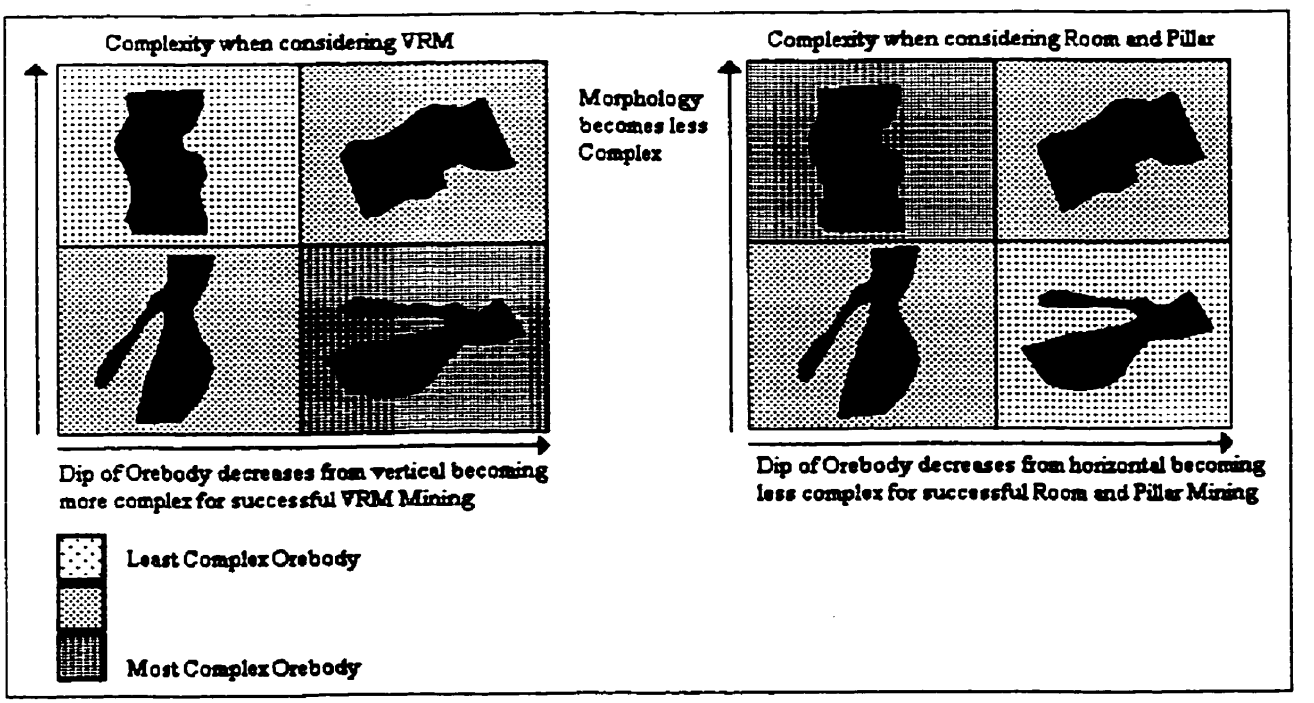


Figure 4.2.1.2 The combined effect of orebody shape and dip on the morphological complexity (after Francis et al, 1997).



Paventi (1990) states that mineral tons and grade in a reserve is a function of the irregularity of the ore/waste contact and the density of the information. Puhakka (1990) reported that the copper grade in different orebodies at the Viscaria Mine is lower for complex orebodies than those with straight ore boundaries. In this study, data intensity was also shown to influence tons and grade, with the lower grades being found in orebodies defined by holes on a wider spacing. This tended to indicate that more accurate grade assessment occurs with denser information, particularly where complex orebodies are concerned. This is further demonstrated in the application of geostatistics. Geostatistics was purposefully designed such that they allowed for the calculation of a measure of the error associated with grade and tonnage estimates. The procedure used is that of kriging which allows the reliability associated to be influenced by the variability of the orebody and the accuracy and intensity of the drilling. Thus with any estimate a variance is produced. A large estimation variance relative to the estimate implies a poor estimate and vice versa. In this manner kriging variance ranges produced, demonstrates the range in variability from simple to complex.

The complexity index can be considered in both two dimensions (section and plan) as well as three dimensions (refer to figure 4.2.1.1). The dip of an orebody also has a significant effect on its complexity from the viewpoint of mining. It therefore is also considered as an element of morphological complexity. The size of this effect is a function of the type of mining method proposed. For instance, mining methods requiring the aid of gravity to move blasted rock are suited to, and perform more effectively on, steeply dipping orebodies. Thus should such a mining method be applied to a shallow dipping orebody it will exhibit a low performance.

Dilution in VRM stopes, at Thompson Mines, has been attributed to a number of factors, including the inability of long blastholes to envelope thin, sinuous orebodies without including waste. The same was reported at Lynn Lake where Ruttan (1968) reported that the 12.5 percent dilution accompanying longhole stoping was directly related to the irregularity of the orebody.

Figure 4.2.1.2 describes the combined effect of orebody outline and dip on the morphology and complexity index.

4.2.2 Grade Complexity

Grade complexity (Figure 4.2.2.1) refers to the grade distribution within an orebody. Simple distributions, e.g. a uniform distribution, would be less complicated to mine in order to maintain consistent mill head grade. However, if the orebody is such that the grade distribution is erratic, other than the problems it creates for delineation, then it also complicates the mining method. More involved stope sequencing, stockpiling and blending may be needed to achieve a consistent mill head grade.

This is often more acute in precious metal deposits such as the gold mine, Campbell Mine, Ontario, where a nugget effect is created. High grades are achieved of 20.5 grams per tonne, but this is not evenly distributed about the ore but as native gold in veins. Thus erratically dispersed the ore is hard to delineate and achieving a consistent mill head grade such that all the gold is retrieved and not sent to the tailings pond is difficult.

Figure 4.2.2.1 Grade Complexity (after Francis et al, 1997)

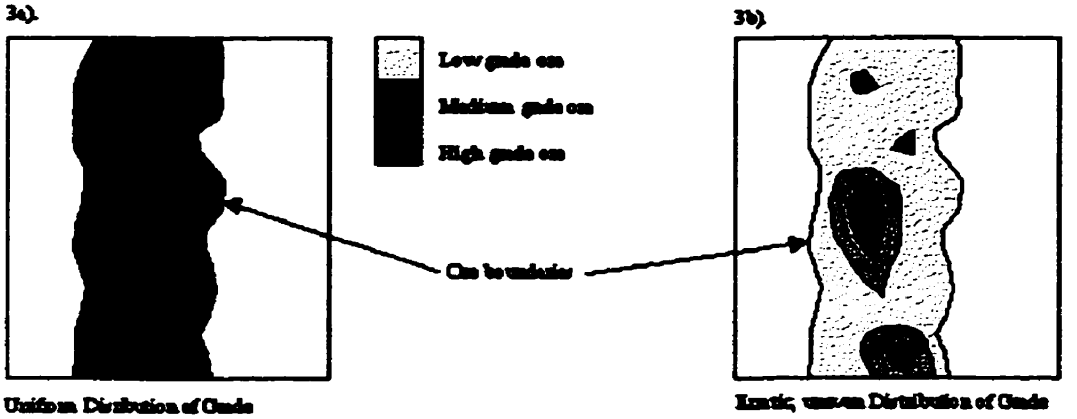


Figure 4.2.3.1 Geotechnical Complexity (after Francis et al, 1997)

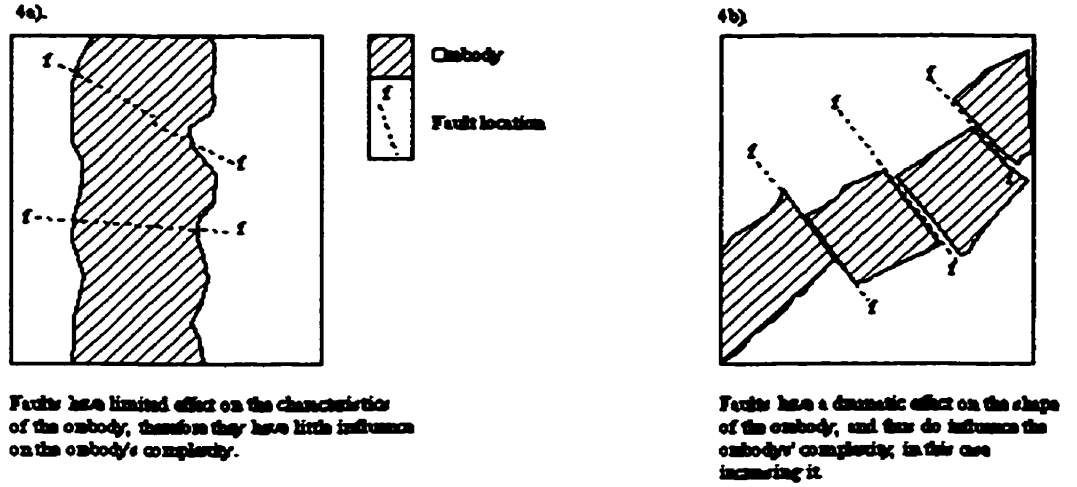
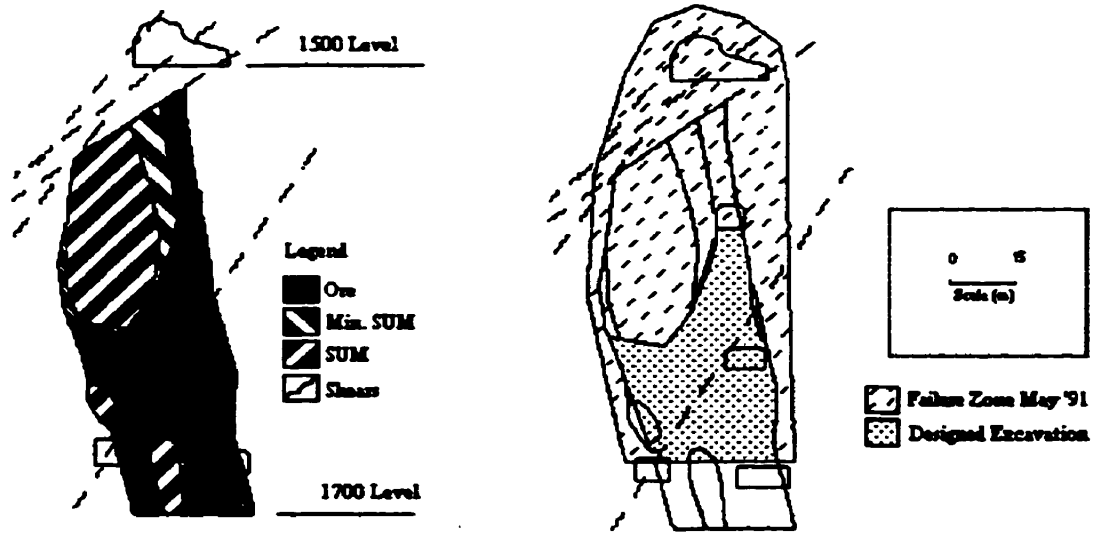


Figure 4.2.3.2 Geotechnical Complexity (adapted from Paventi et al, 1995)



4.2.3 Geotechnical Complexity

The orebody and host rockmass geotechnical characteristics (Figure 4.2.3.1) are an important aspect of orebody complexity for several reasons. Geotechnical characteristics can influence; the emplacement of the ore, its quality, the ground conditions and the type of mining that is most suitable. Discontinuities, shears and faults play a role in the emplacement and remobilisation of mineralization and thus effect the location of ore as well as ground response to mining. According to Boyd (1988), discontinuities of unfavourable orientation are directly responsible for many kinematic or gravity failures in underground mines.

Faults that have little displacement, as illustrated in 4.2.3.1a., may not complicate the orebody characteristics and thus will add little to its complexity. The fault orientation and strength, however, may control stope stability and ground stress redistribution as well as groundwater regime.

Faults can significantly affect the location of the ore, increasing the complexity, see 4.2.3.1b., where the morphology has been complicated by faults. Geotechnics is critical in the consideration of stope design and the support required for particular mining methods.

Component geological units in a rock mass may pose particular geotechnical complexity. The presence of peridotite, for example, within nickel-hosting deposits in Manitoba have been observed to increase complexity. The peridotite often sits in the walls adjacent to the ore as well as internally. It often represents a very weak rockmass, with the risk of collapse when the ore is extracted, thus increasing dilution.

Figure 4.2.3.2 shows how contrasting rock mass structure and strength can control the effectiveness of a mining method. In this example the presence of weak peridotite bodies (SUM), within and adjacent to nickel-hosting orebodies at the Birchtree Mine increased the geotechnical complexity significantly.

4.2.4 Ore mineralogical characteristics

This parameter refers to the mineralogy of the ore. Some ores are mineralogically complex and present challenges to full and efficient recovery in processing. Some minerals are also deleterious to mineral processing or smelting, whilst others are susceptible to weathering and pose problems for subsequent processing.

Deleterious minerals extracted with ore, such as talc and gesdorffite, often associated with nickel ore, may prove too costly or harmful to attempt to process. If such deleterious mineral zones are randomly distributed then the orebody complexity is increased, challenging any attempt at selective mining. Oxidation-prone minerals within ore can also increase the orebodies complexity if the desired mining process requires the ore to accumulate in stockpiles, stopes or ore passes prior to processing. Both oxidation and spontaneous combustion can also reduce the diggability of the ore and its handleability in transit. Abrasivity resulting in an ore from particular mineral assemblages can also add orebody complexity. Wear on mining equipment then can become a significant issue depending upon the nature of both the equipment and material, e.g. bucket wheel tooth wear in oil sands, bit wear in iron ore.

4.3 Complexity Index

The complexity index is aimed to provide a preliminary estimate of orebody complexity, relative to a particular mining method. It is therefore required to weight the importance of morphology, grade distribution, geotechnics and ore mineralogical characteristics in terms of their influence on mining method performance. The complexity index can be represented as:

$$CI = f(m_i, gd_i, gt_i, mc_i)$$

where CI = Complexity Index

m_i = morphology index

gd_i = grade distribution

gt_i = geotechnical characteristics

mc_i = mineralogical characteristics

In this thesis the work was confined to consideration of the morphology index of an orebody, m_i.

By eye, one tends to perceive outlines to be more complex the more irregular they appear to be. Irregularity can be defined as the rate of change of curvature of a line, the more variation in curvature that occurs in the line the more complex it is. To calculate m_i, it was therefore required to account for curvature.

4.4 Previous Attempts to Produce an Index for Orebody Morphology

Carras (1987), proposed a classification of ore deposits which took into account the geometry, the grade distribution and the coefficient of variation of the assay population. The coefficient of variation is equivalent to:

(Standard deviation of the Assay population * 100)/ Mean of the Assay Population

Annels 1991, summarises the classifications as described in table 4.4.1:

Table 4.4.1 - Carras' Classification (adapted from Annels, 1991)

Type	Geometry	Grade Distribution	Coefficient of Variation	Examples:
Type A1	*simple*	*simple*	*low*	Coal, iron, bauxite, lateritic nickel and stratabound copper
Type A2	*simple*	*complex*	*low*	Disseminated copper, gold stockworks, Witwatersrand gold
Type B	*complex*	*simple*	*low*	Base metal deposits, e.g. skarn copper deposits (Craigmont, BC)
Type C	*complex*	*complex*	*high*	Archaean gold (e.g. Kalgoorlie and the Abitibi Greenstone Belt of Canada)

Type A

Carras indicates that only minor dilution is likely to take place during mining. These orebodies are easier to predict and the use of either statistics or geostatistics provide similar results and are believed to be true of the deposit.

Type B

These orebodies tend to have irregular margins, leading to high edge dilution. Their complex geometry makes them harder to predict, particularly with the application of geostatistics.

Type C

These deposits have internal and edge dilution due to the patchy nature of the mineralization and its ill defined or irregular envelope. Carras states that classical ore reserve methods are best applied in such deposits, although they often give large margins of error.

Carras recognised the importance of complexity in relation to how it affects the application of reserve calculations through geostatistics and statistics, considering both the parameters of geometry and grade distribution. His classification, with its very broad categories, is useful for conceptual distinctions between different ore deposits, but for distinguishing orebodies within a similar environment the classification is too generalised.

Prior work at Inco's Thompson Mine, attempted to determine the accuracy of ore interpretation and its relationship to dilution, but did not consider grade variability or geotechnics (Braun, 1991). In this case an index was sought that, unlike Carras,' would be able to distinguish between orebodies within a similar environment at a higher level of detail. For thirty geological sections, sublevels were laid out with a common vertical interval of 30 metres (100 feet), and three separate hypothetical cases for each section were generated: with no diamond drilling on section; 15 metre (50-foot) interval diamond drilling; and with 7.6 metre (25-foot) interval diamond drilling on section. For these sections he collected a number of interpretations (based on standard procedures) to then compare actual cut and fill stope geology to the interpreted geology. Based on these results loss of ore and dilution could be estimated assuming a bulk mining method had been applied instead of the more selective, actual cut and fill.

Braun determined that he had to firstly classify the sections by geometric complexity. The method utilised was based on comparing a straight line drawn from the ore/waste contact at the bottom of the top drill room to the ore/waste contact at the top of the mucking sublevel.

This is shown in figure 4.4.2. This was done for both the hanging wall (HW) and foot wall (FW) sides of the orebody where the areas enclosed by the actual FW/HW and the FW/HW straight line were then determined. These two areas were then totalled and prorated for each 30 metres (100 feet) of straight line. In order to produce the index the areas were simply divided by 100. All areas greater then 6 received an index of 6.

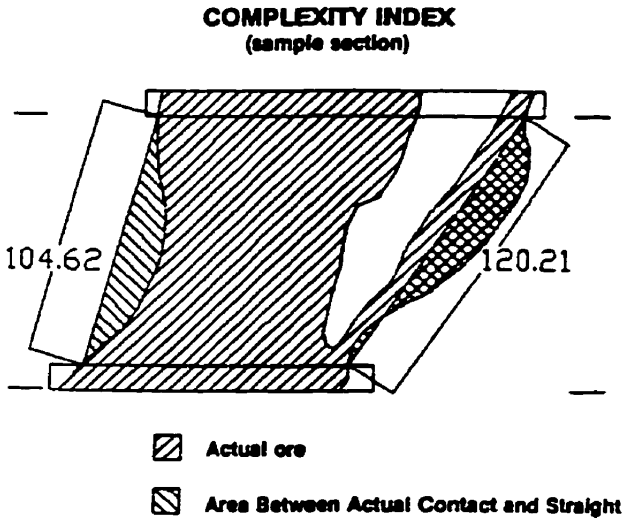
Problems with Braun's Index lie in the fact that only the exterior walls were considered, thus orebodies whose geometry/morphology are complicated by large inclusions of waste rock do not show a larger complexity index. For example, the two sections (Figure 4.4.3 and 4.4.4) would provide the same complexity index, yet they are clearly of different complexity from the viewpoint of mine design.

Thus for the purposes of determining a morphological index, it must be capable of quantifying the irregularity of the perimeter of an orebody section, including all exterior edges not just the foot and hanging walls. It should be a measure which distinguishes between similar orebodies in the same ore deposit environment, for example between the various orebodies located within the Thompson Nickel Belt.

4.5 Analysis

Data was collected in the Thompson Nickel Belt, from Inco's Manitoba Division. The cross-sections collected were cut and fill stoped cross-sections. It was thus assured that the most reliable, available geological detail related to each orebody was used. Consequently the method selected for quantifying morphology would be tested based on as true an orebody outline as possible. In clarification, an orebody outline drawn based on a limited amount of information from diamond drilling would not produce a true orebody outline also, due to the limited data density the outline would tend to be less irregular and smoothed.

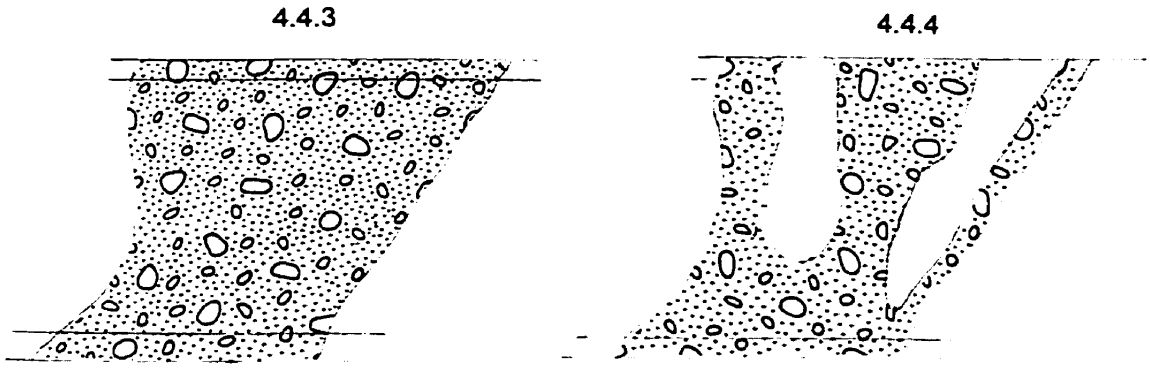
Figure 4.4.2 The methodology behind Braun's Index (adapted from Braun, 1991).



Area Between Contact and Straight Line		
Hanging Wall	1053.83	(rock)
Footwall	1058.24	(ore)
	38.85	(rock)
Total	2150.92	sq. ft.
Length of Straight Line		
Hanging Wall	104.62	ft.
Footwall	120.21	ft.
Total	224.83	ft.

Complexity (per 100 ft. of straight line)
➢ 2150.92 / 224.83 * 100 = 956.69

Figure 4.4.3 and 4.4.4 Problems associated with Braun's' Index - the exterior walls of an orebody are considered only.



Measuring the exterior edges would provide the same complexity index for both 4.4.3 & 4.4.4. It is clear however that 4.4.4 is more morphologically complex.

In order to understand the morphological relationship to geology, the more than 150 sections collected were taken from very separate orebodies at different mines in Inco's Manitoba Division. It is important to mention here that the sections were all cross-sections and thus the morphological measure found and applied would in affect be providing two-dimensional information relating to morphology only. Examples of the sections utilised are provided in figure 4.5.1. Variations between cross-sections therefore reflect the three-dimensional variability of the morphological complexity.

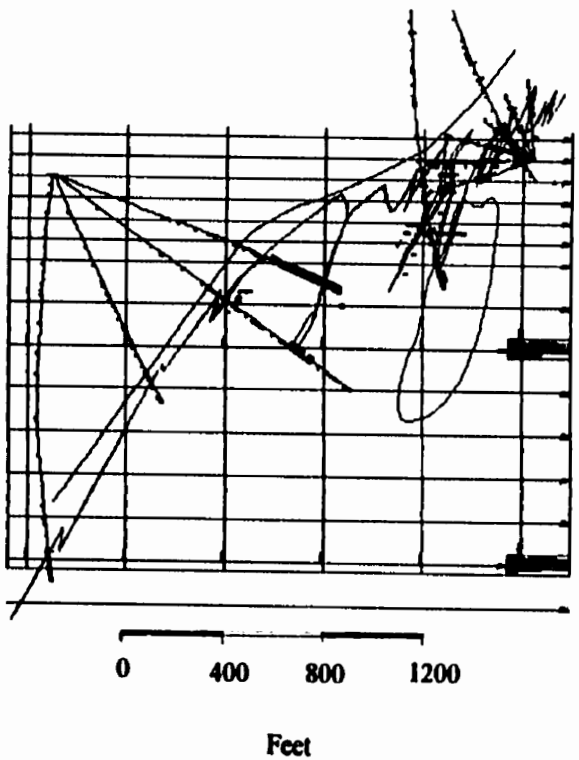
Once a means of determining the morphological index had been determined then it was important to evaluate this and validate the approach by testing the measure on other sections representing different orebody types and very different morphological styles. Sections for this purpose were collected from a number of Inco's Ontario Division mines in Sudbury. It was important to obtain sections of the same scale, otherwise the 'scale effect' would bias results. Figure 4.5.2 illustrates the impact of this scale effect. Figure 4.5.2 a. describes the view of an orebody from a great distance, whilst figure 4.5.2 b. and c. describe the orebody at increasingly closer perspectives. It is clear from this example that, depending on scale, very different morphological complexities are viewed.

4.6 The Morphological Index Measure, m_i

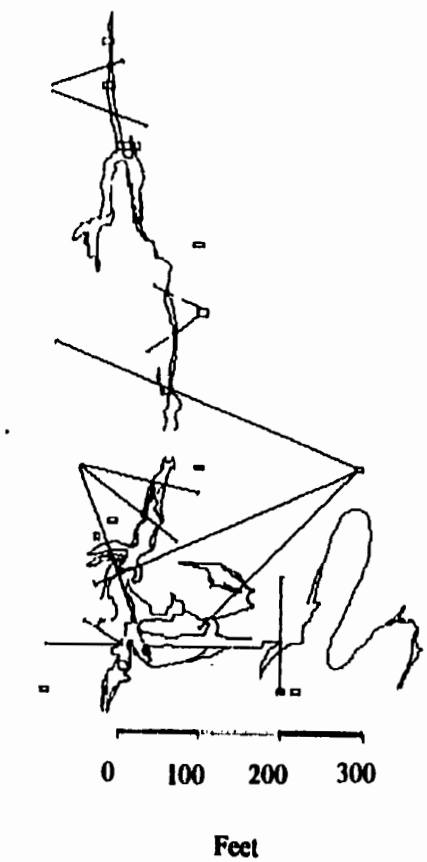
Initial approaches to calculate m_i utilised perimeter length and change of width of the orebody about a central axis. The problem faced with such a method mainly involved the time consumed in measurement and calculation through the use of a scale meter. CAD software was not appropriate where such operations were required on the same cross-section at numerous scales to determine the type of differences brought about by the scale effect. CAD software remembers all details of the digitised sections regardless of the scale viewed. It was thus only used at a later stage for the purpose of validating measurements.

Figure 4.5.1 Examples of sections utilized in analysis of Morphological Complexity from Inco Manitoba Division, Thompson Mines.

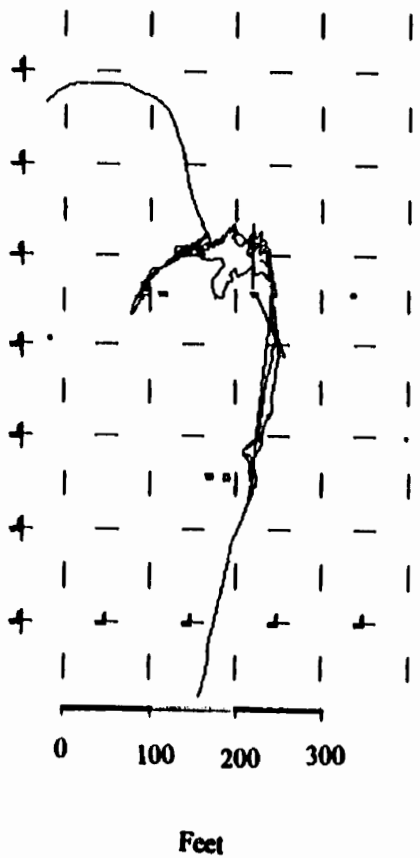
Thompson (T3) 1D Orebody



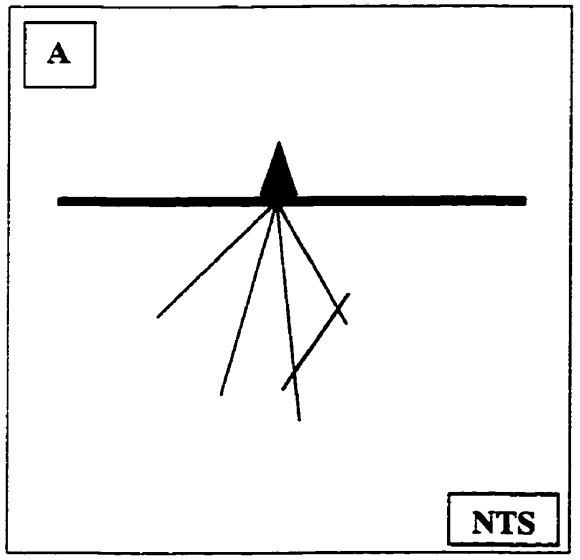
Thompson (T1) NOSE Orebody

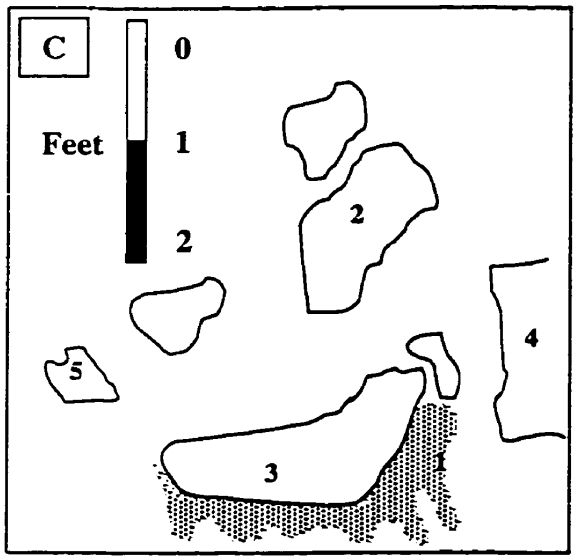


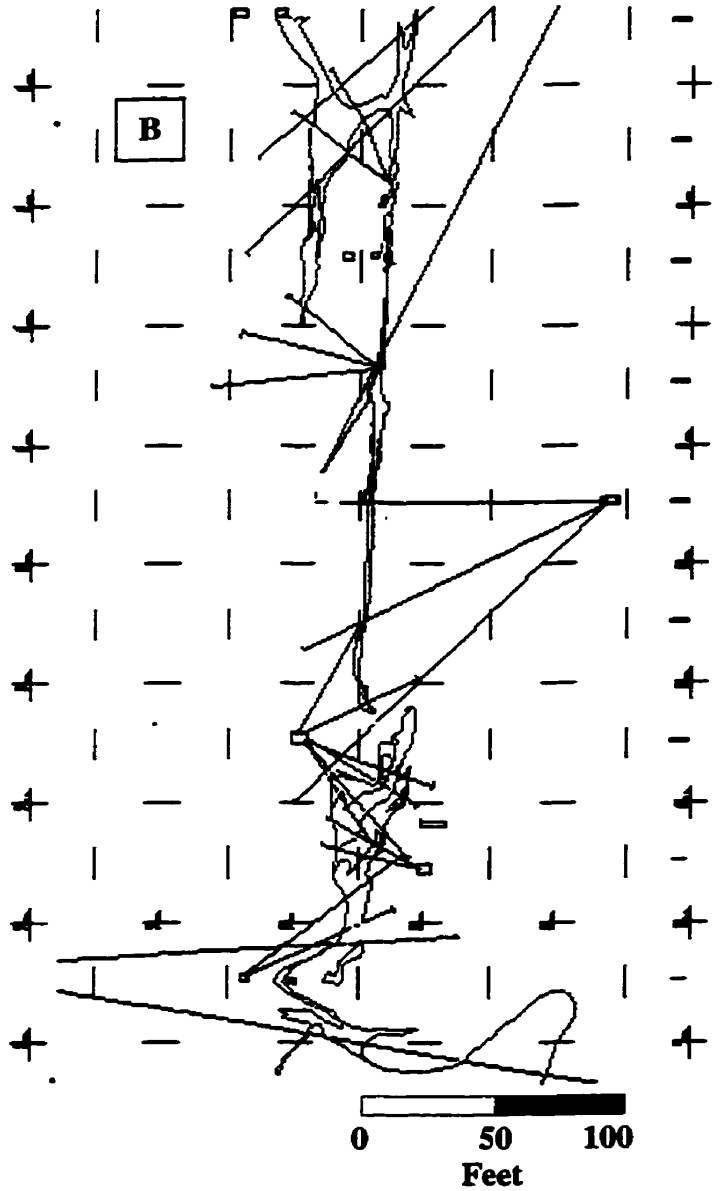
Thompson (T1) 3SHEAR Orebody



Figures 4.5.2 a, b and c - illustrate increasing morphological complexity with increased magnification of orebody.







1. Nickelite
2. Pentlandite
3. Pyrrhotite
4. Biotite Mica
5. Quartz

The alternative pursued was commercial image analysis software, SigmaScan / Image™, originally designed for use in the medical industry and now used for alternate purposes by Dyno Nobel for blast fragmentation analysis (Pers. Comm. Preston, 1997). Figure 4.6.0.1 shows an image of a rat's lung whose image characteristics can be measured by the software. This figure also clearly resembles the orebody outlines described in the previous figure 4.5.1, and thus the transferable technology offered by SigmaScan Pro was evident. The benefits this package offered were ease of use, accuracy and speed of object measurement. Once an orebody outline is inputted into the package then it can be trained to trace the perimeters of an object. Thus the speed of image measurement is extremely rapid when the training of the software has been completed. Based on experimentation, the following measurements were utilised for the Morphological Complexity Index: Shape Factor and Compactness.

4.6.1 Shape Factor

This quantity measures how circular an object is. Shape Factor is calculated as:

Shape Factor = 4π Area / Perimeter^2

A perfect circle has a shape factor of 1.0, and a line has a shape factor approaching zero. For reference, the shape of an equilateral triangle is 0.61, for a square it is about 0.79, and for a pentagon it is about 0.86. Figure 4.6.1.1, describes how Shape Factor changes as a rectangle becomes more circular.

4.6.2 Compactness

This parameter is closely related to the shape factor; it is used for comparing the aerial density of different objects and is calculated as:

Compactness = Perimeter^2/ Area

In the absence of digitisation errors, the minimum compactness value an object can have is 4π (about 12.6) for a circle. As an object's value tends towards a line, then its compactness approaches infinity. Figure 4.6.2.1, describes the progression of the Compactness Factor from a circle to a more irregular outline.

Figure 4.6.0.1 Diagram of Rats Lung using Sigma Scan Pro™ -note its similarity in shape to Figure 4.5.1

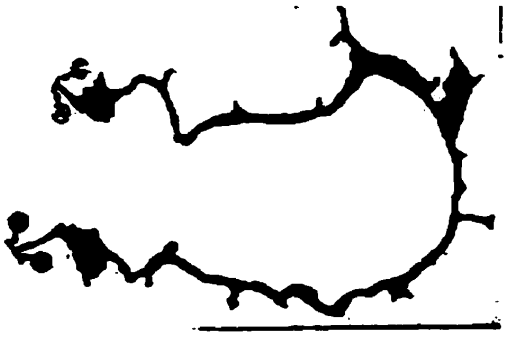


Figure 4.6.1.1 The Shape Factor Illustrated

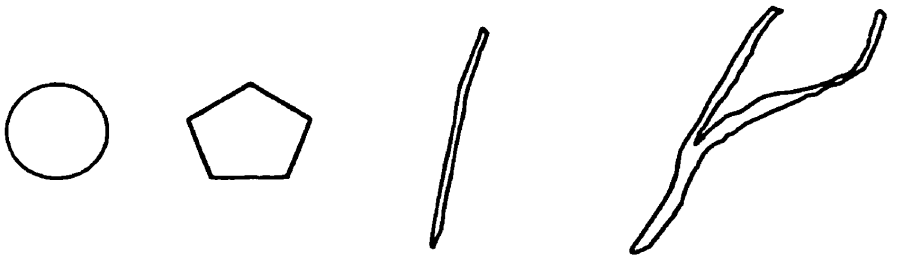
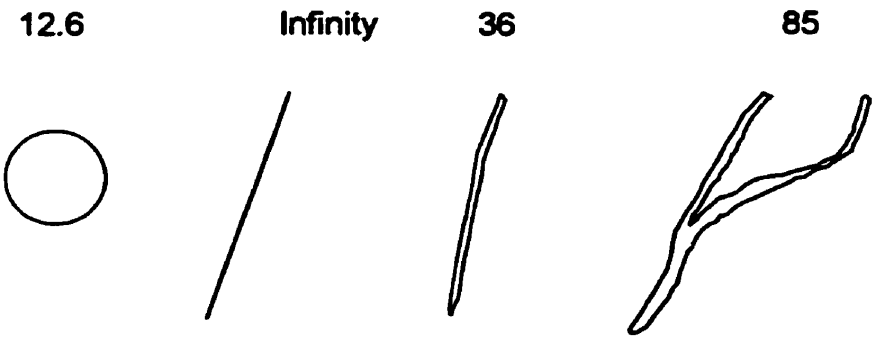


Figure 4.6.2.1 The Compactness Index Illustrated



4.7 Validation of the measures

In order to validate the Shape Factor and Compactness as useful measures for m_i, the sections utilised by Braun (1991) in his evaluation of Ore Interpretation Accuracy were used. In this case the following methodology was applied:

1. Sections were digitised into AutoCad™.
2. Sections were then exported as bitmaps and opened in SigmaScan / Image™.
3. Once the sections were calibrated, then the measurements required were selected.
4. A tracing tool was then used to trace the edge of the section and calculate automatically the defined parameters to be calculated which were placed in a worksheet and then a spreadsheet.
5. Within the spreadsheet or within an external graph package a scatter graph was then produced to compare Compactness and Shape Factor values. Based on this scatter graph and identification of points, the adequacy of the factors for evaluating m_i could be found. The graph allowed human judgement of cross section complexity to be validated. Thus sections perceived by eye as simple, should be located in the lower right hand side of the graph, and those perceived as complex should be in the left hand corner, if the index was effective.

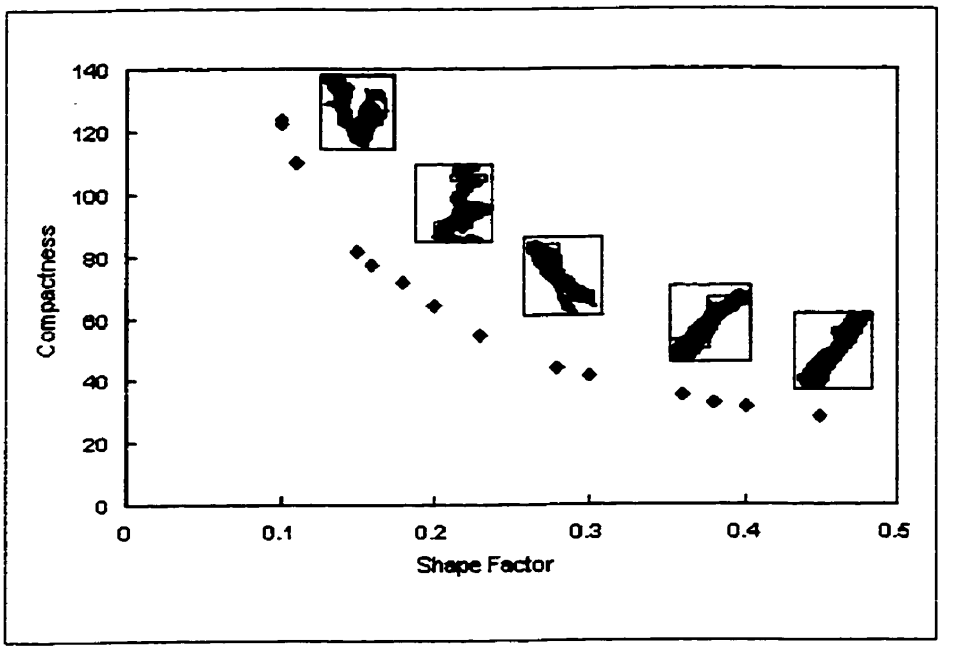
In the context of this application, Compactness describes how linear an orebody is, whilst Shape Factor describes how much the orebody resembles a circle. The more regular and elongate an orebody, then the more linear it appears and the less it resembles a circle, thus it has a low Shape Factor and a high Compactness value. Irregular orebodies with contorted exterior edges and lack of linearity conversely exhibit low compactness and high shape factor values.

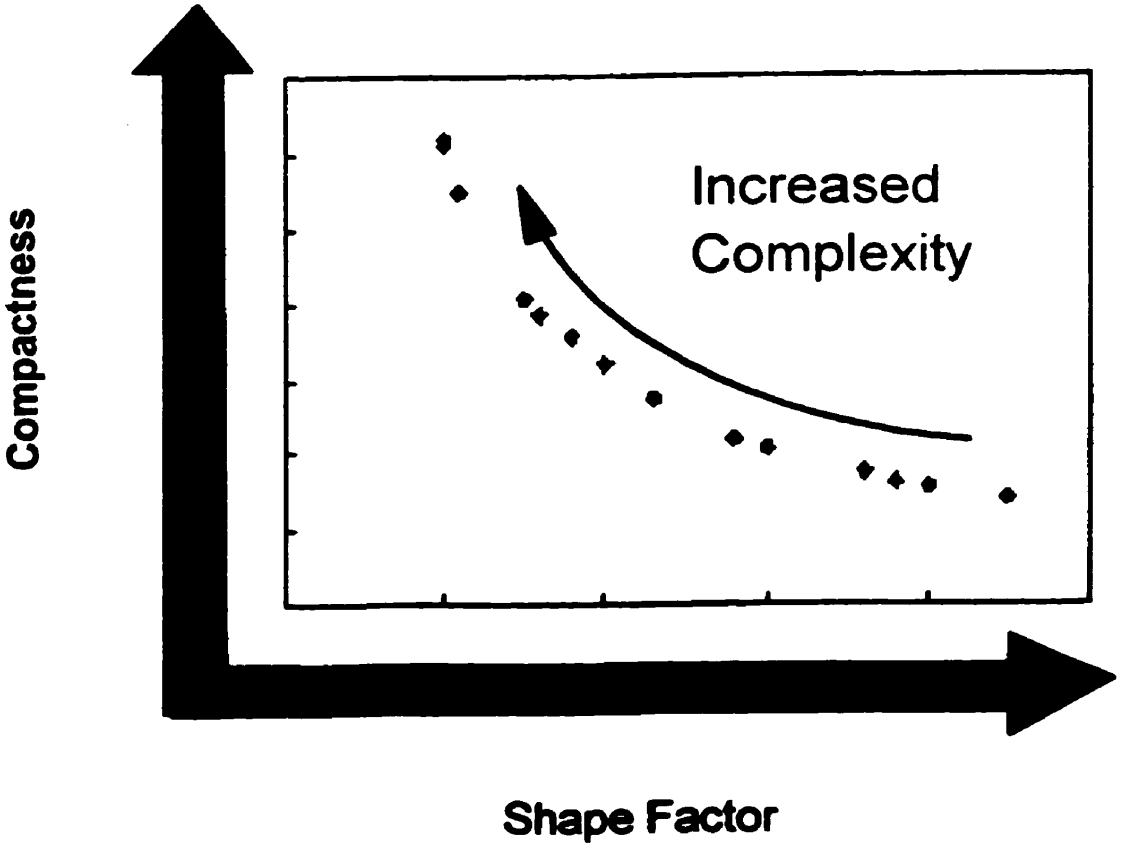
4.8 Validation of Results

The results are summarised (figure 4.8.1) in graphical form, combined with diagrams of the representative section for that region. It shows how, with increasing Shape Factor the section complexity increases. Since area and perimeter are utilised in these functions then the comparison can be made between sections of varying height and width.

For purposes of the m_i calculation only one of these parameters need be used, since both involve manipulation of the same factors, i.e. area and perimeter. However, in general the orebodies represented at the Thompson mines are broadly similar in that they are narrow, elongate and steeply dipping. It was determined that the Compactness value which compares a shape to a line would allow a clearer distinction between these broadly similar orebodies and thus was the more suitable measure to employ. The following chapters discuss the morphological complexity found for Inco's Manitoba and Ontario Division orebodies, such that an orebody classification system could be built and the influence of orebody class on mining method performance measured.

Figure 4.8.1 Results used for validation of the morphological complexity measures - based on Braun's sections.





CHAPTER 5 - MORPHOLOGICAL COMPLEXITY

5.0 Morphological Complexity

This chapter reviews the data collected and analysed from both Inco's Manitoba and Ontario Division Mines. For each region the general geology is discussed and the results of the Morphological Index are presented for the orebodies from each mine. The results are then related to the geological environment of each orebody such that a final classification of the orebodies can be produced. This classification aims to relate the morphology of an orebody to its anticipated morphological index and geological characteristics.

5.1 General Geology of the Thompson Nickel Belt

The Thompson Nickel Belt is a linear north-east trending tectonic feature, approximately 10-35 kilometres wide, for a length of 200 kilometres. Figure 5.1.1 describes the regional geology of the Thompson Nickel belt, adapted from Paventi (1995). Historically the belt has held many of Canada's major mineral deposits. It is situated on the boundary between the Superior and Churchill Provinces (Bleeker, 1990). Comprised of mainly gneiss's, metasediments, metavolcanics, ultramafic rocks and felsic plutons, the belt ranges in age from Archaean to early Proterozoic. The serpentinised ultramafics (SUM) and metamorphic rocks are confined to the western side of the belt which holds the known nickel deposits (Paventi, 1995). As reported by Bleeker (1990) the belt is highly deformed, thus creating thin, sinuous orebodies, generally smaller than the minimum mining width (Paventi, 1990).

5.1.2 The Manitoba Division Mines

The Manitoba Division Mines consist of inactive mines (Pipe, Soab etc.) and the existing mines (Thompson's T1 and T3, Birchtree). For this thesis the existing mines were considered. Figure 5.1.2.1 describes the orebodies in the Manitoba Division in plan, whilst Figure 5.1.2.2 describes the orebodies in perspective. Each mine comprises a number of different orebodies (e.g. at Thompson T3 mine 1C, 1D etc. orebodies are found), which are located at various positions about a fold structure. It is believed, as explained later, that it is this structural control which greatly influences the morphological complexity of each orebody.

Figure 5.1.2.3 illustrates a generalised cross section from the Thompson Mine, where it can be seen that a narrow ore zone lies between schist, quartzite and gneiss. The ore zone tends to be steeply dipping throughout the mine at an average of 70 degrees to the south east. It is thus suited to gravity induced extraction methods, this combined with the desire for high levels of production encouraged Inco Limited to move to a bulk mining operation, vertical block mining (VBM) from cut-and-fill mining through the eighties.

Bleeker (1990) reported that seven fold and seven fault generations have been established in the belt, five fold generations being exhibited in the Thompson Mines themselves. This has resulted in the overprinting of folds, deformation of structures, high grade metamorphic conditions and the development of faults. Through these events the orebodies have suffered from much boudinaging and the tight folding and development of isoclinal folds. The boudinaging, as illustrated in Figure 5.1.2.4, creates deformation in the metamorphic rocks, in which originally rigid (competent) bands or layers between relatively plastic (less competent) layers are stretched and thinned until rupture occurs. The rigid bands are then caused to separate into long cylindrical pieces, resembling a 'string of sausages'. Where these bands are not completely separated the structure pinches and swells out. In the Thompson Nickel Belt the massive sulphide is more competent than the surrounding schist's and hence the boudinaging occurs.

Peridotite the generic name given to the serpentinised ultramafic units (SUM) by both geology and mining engineering staff in the Manitoba Division, form 'balls' pinching and swelling as a result of this boudinaging in section and plan (Paventi, 1995).

The consequence of this structural complexity is increased orebody complexity. Platford et al (1991) report that mineral widths vary from 1.5 metres (5 feet) to over 24 metres (80 feet) with the ore zone containing rock inclusions of 10% to 70%. A series of tight joints and joint sets are present in both the ore and adjacent rock, commonly along the direction of foliation, which during blasting can accentuate breakage. Plate 5.1.2.5 illustrates the foliation of the ore seen in the Birchtree Mine. Three mines were considered during the research: Thompson Mine (T1) and (T2) and Birchtree Mine. A representative selection of orebodies was made from each of these mines as described below:

- Birchtree - 83 Orebody

Figure 5.1.2.6 describes the location of the 83 orebody at the Birchtree mine in plan. Unlike many of the orebodies at Birchtree, it suffers more from instability associated with the SUM units, in comparison to other orebodies associated with SUM units. Peridotite appears as oblong-shaped in plan and section, varying in width from a few centimetres to 10's of metres, (Paventi, 1995). In the 83 orebody, however, being towards the south of the Thompson Belt, it contains many peridotite and other rock inclusions. The massive sulphides of the orebody tend to concentrate between the footwall and the SUM zone, although it is not uncommon for the massive sulphide to completely encompass the SUM in orebodies further north in the mine. Figure 5.1.2.7 and Plate 5.1.2.8 illustrates peridotite bodies which are encompassed by ore in the 108 orebody further to the north of the mine.

Figure 5.1.1 The regional geology of the Thompson Nickel Belt (after Bleeker, 1990)

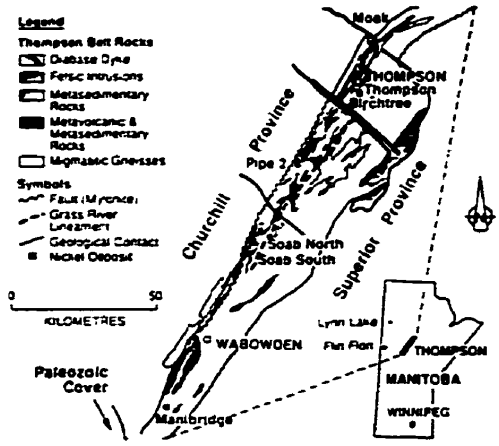


Figure 5.1.2.1 Orebodies in Inco Manitoba Division, shown in plan (after Platford et al, 1991)

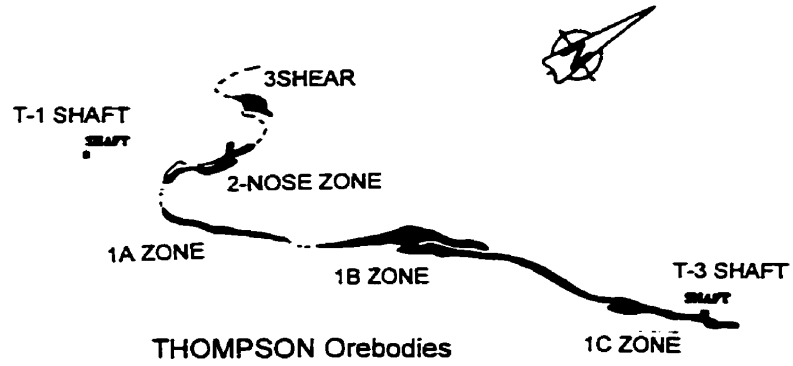


Figure 5.1.2.2 The Inco Manitoba Division orebodies illustrated in perspective (after Bleeker, 1990)

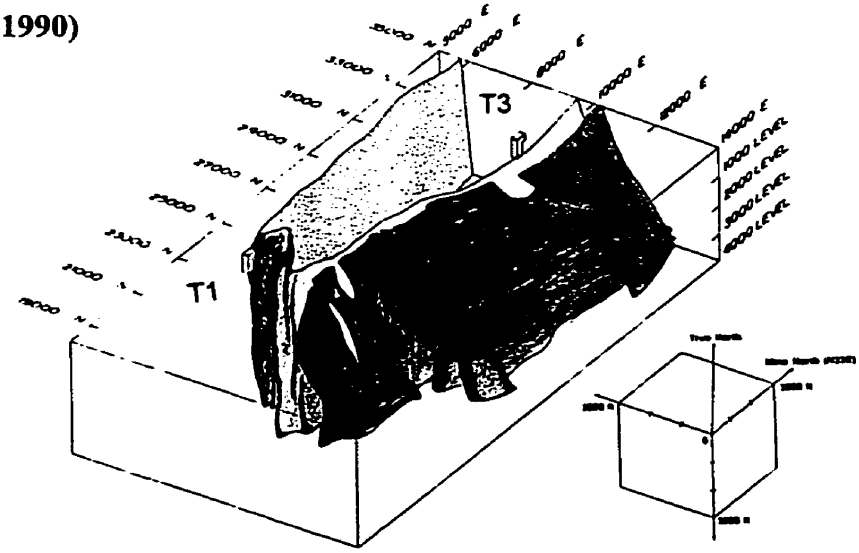


Figure 5.1.2.3 A Generalized Cross Section from the Thompson Mine (after Platford et al, 1991)

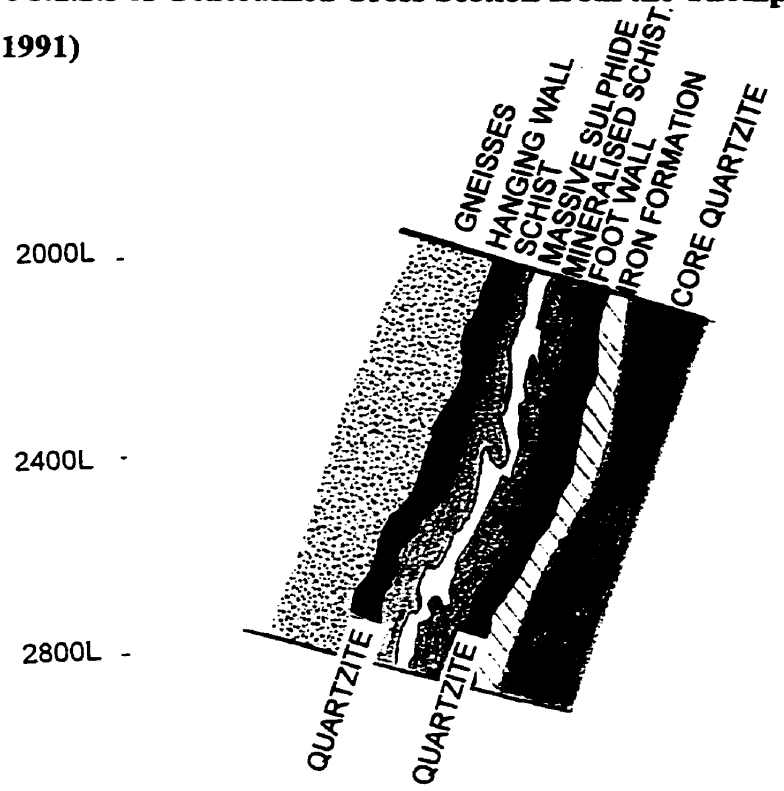
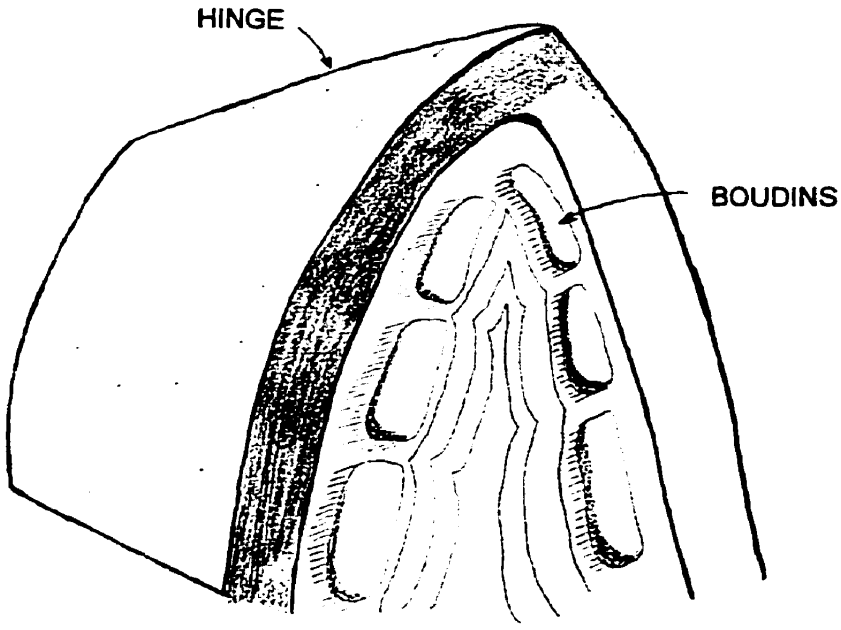


Figure 5.1.2.4 The effects of boudinaging



Paventi (1995) reported distinct characteristics in all the orebodies at Birchtree in relation to their location: in section the massive sulphides appeared to lie along the base of the SUM zone, whilst in plan the sulphide flanked, one side of the SUM and occasionally encompassed it. These characteristics are described in Figure 5.1.2.8, using section and plan illustrations from the 83 orebody.

Plate 5.1.2.5 Foliation of the orebody at Thompson

Figure 5.1.2.6 The Birchtree Mine orebodies in plan (after Paventi, 1995)

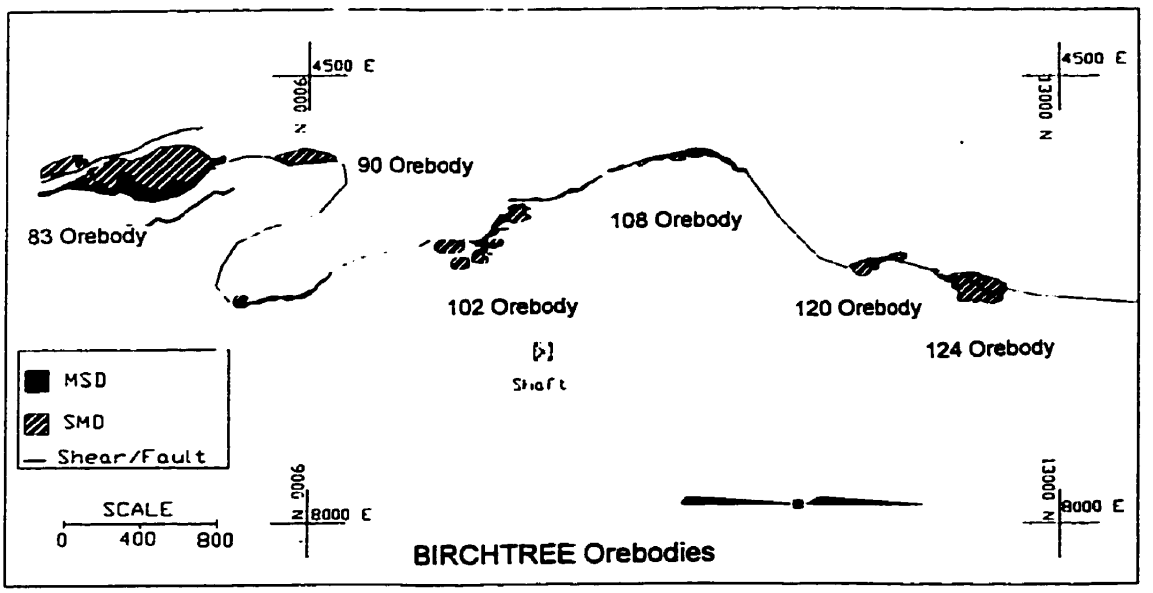
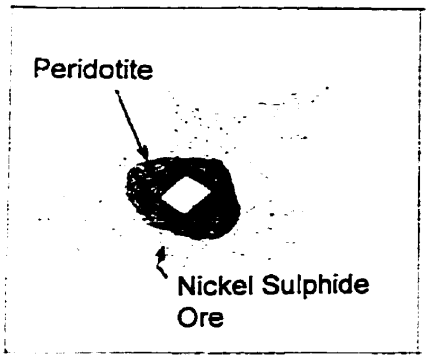


Figure 5.1.2.7 and Plate 5.1.2.8 Peridotite bodies present as inclusions in the Birchtree Mine orebodies



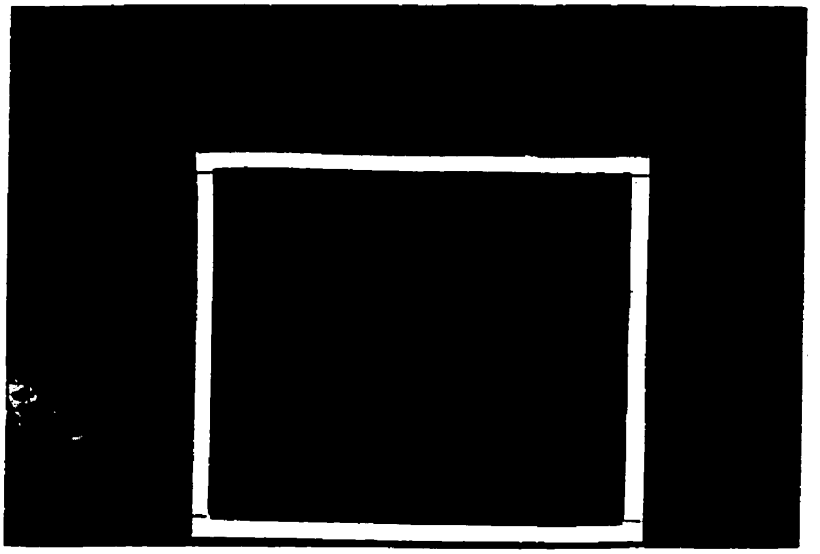
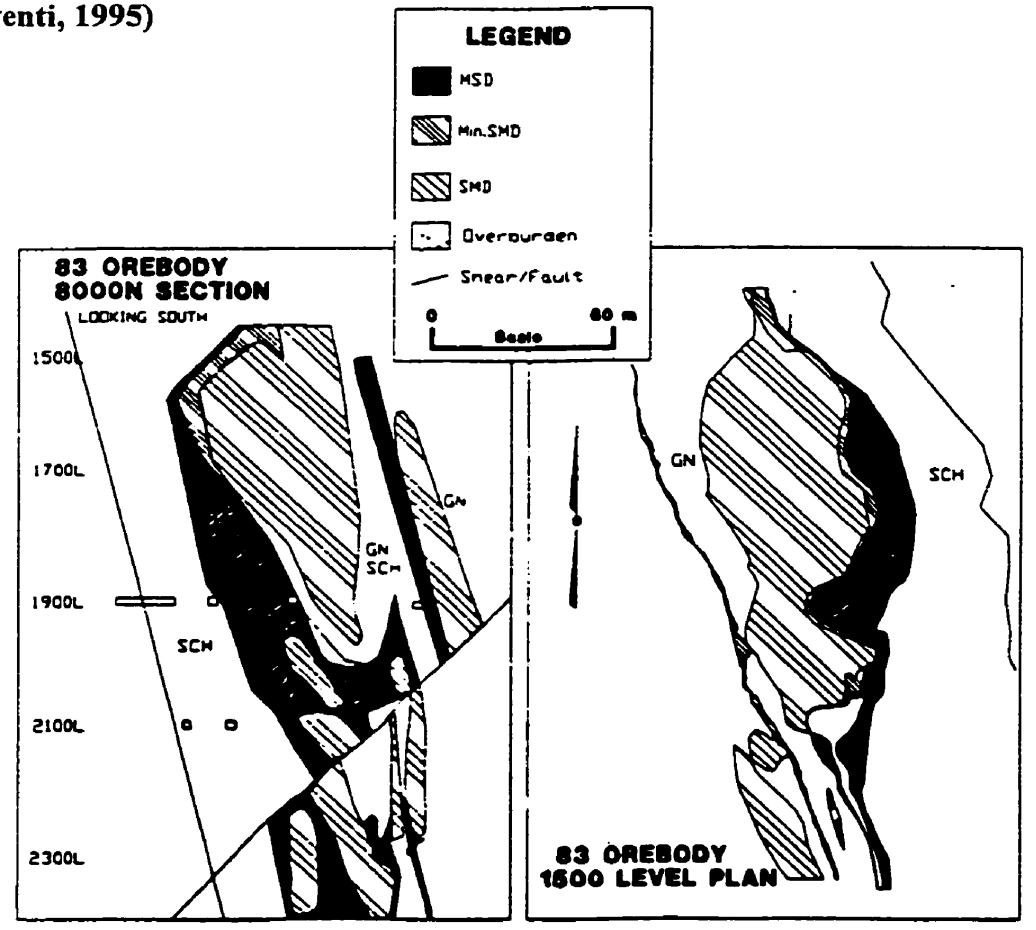


Figure 5.1.2.8 Section and plan views of the Birchtree Mine 83 orebody (after Paventi, 1995)



- Thompson (T1) NOSE orebody

  As illustrated in Figure 5.1.2.6 the orebody takes its name from its location, which is at the nose of a fold. This region is generally less effected by peridotite inclusions, which create instability. However, the zone does suffer from similar instability mechanisms but stability is greater due to the reduced size, abundance and spatial distribution of the SUM bodies. The location of the orebody at the nose has resulted in dilation of the nickel sulphide ore (Pers. Comm. Paventi, 1996), thus cross sections through the orebody depict the familiar boudinaged orebodies, yet in this case at its base the orebody is contorted and appears to fold back on itself (see figure 5.1.2.9).

- Thompson (T1) 3 Shear orebody

  Located on the limbs of a fold, the 3 Shear is less contorted than the NOSE. As with all the orebodies in the Thompson mine, compared to those of the Birchtree Mine, peridotite inclusions are less extensive and abundant. However for a Thompson mine 3-shear exhibits numerous SUM inclusions. It can be described as a microcosm of Birchtree, facing similar caving problems. This orebody receives its name from the fact that its major characteristic is localised shearing. The shears are typically chloritic/graphitic and slickensided, indicating that movement has taken place. They can create instability problems.

- Thompson (T3) 1C Orebody

  Refer to Figure 5.1.2.6 for the location of the 1C orebody in plan. The main source of geological complexity occurs as a result of shearing and faulting exhibited in the orebody, primarily as a result of the quartz, carbonate filled Davies' Shear fault. The consequence has been that, although the ore/ waste contacts are well defined, with less peridotite bodies, than witnessed at the Birchtree Mine, the dilution suffered has been estimated at between 20-25%. This is 6-10% greater than originally designed (Pers. Comm. Owens, 1997). As this orebody is located on the edge of a limb it suffers little dilation and as a result is less contorted than the NOSE orebody.

Figure 5.1.2.9 Example of cross section from the NOSE orebody at Thompson's T1 Mine.

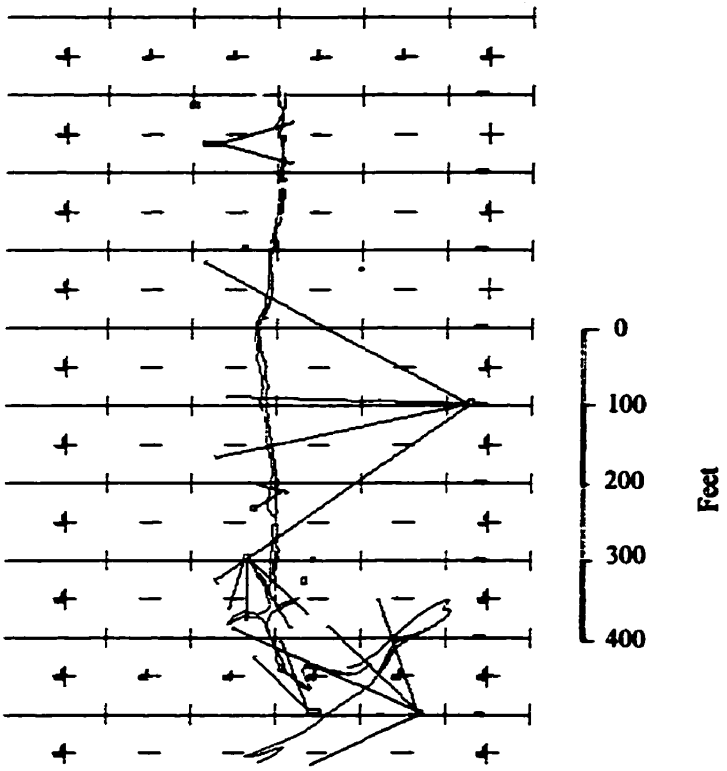
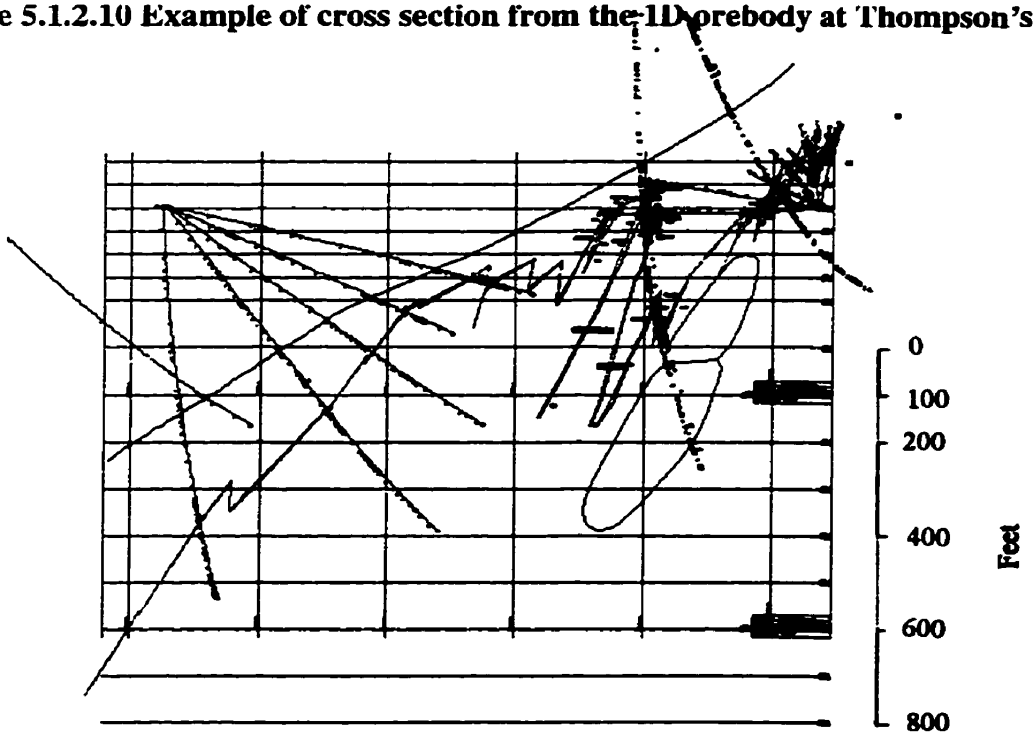


Figure 5.1.2.10 Example of cross section from the 1D orebody at Thompson's T3 Mine.



- Thompson (T3) 1D orebody

  The 1D orebody, the most recently developed Manitoba Division is proving to be one of the most difficult to model. Located deeper and further north west than the 1C orebody, information pertaining to its geology is scarce in comparison to the others studied. After initial delineation drilling it was determined that the ore had either undergone severe tight isoclinal folding or had been faulted heavily. Further knowledge since development began has led geologists to believe that, although folded, the ore has been dilated upwards at the top of the folds, as illustrated in Figure 5.1.2.10. With multiple bands of boudinaged ore, numerous interface patterns have occurred, further complicating the geology, (Pers. Comm. Owens, 1997). A geotechnical problem is added in the fact that it is believed that graphite coats many of the joints and thus they are friable and weak in shear, thus tending to increase stability problems.

5.2 Manitoba Division Orebody Complexity Analysis

The outlines of each orebody sampled were determined according to the interpretation made by the mine geologist in charge of the respective orebodies. Any subjectivity in such decisions to determine orebody outline were not considered herein. It should be noted, however, that orebody morphology can vary depending on the following:

- Geological subjectivity; as to how an orebody should be interpreted
- Economic situation; determining what cut off grade exists. Interestingly this particular parameter may have little or significant effect, dependent on the mineralization style. For example, if an orebody gradually decreases in grade at its perimeters, then the overall morphological shape will remain consistent with each economic situation. In a situation where high grade mineralization offers a very different distribution to that of lower grade mineralization, then as economic circumstances change, a more significant change in morphology may result. The implication of outlining an orebody purely according to cut-off-grade is that its morphological complexity is increased, with the orebody often becoming many small pods of ore.

These factors outlined above are additional to those of information density, quality, and scale parameters, which will also effect the morphological outline. These factors however, are of relatively the same influence in each section measured, due to the fact that the information density tends to be consistent, due to the Manitoba mine sections being constructed based on cut and fill information[1]. Also this Division employs a relatively consistent approach to the manner in which geologists interpret orebodies, and finally all sections measured were considered at the same scale of 2.54 cm = 15 m, (1"=50').

Figure 5.2.1. and 5.2.2 describe the results of the morphological complexity analysis undertaken on the orebodies from Manitoba. Figure 5.2.1 illustrates the range of complexity found for each orebody based on measurements from individual sections. Figure 5.2.2 provides a graphical representation of the data with five statistics in summary; i.e. minimum value, 25% quartile, median, 75% quartile and maximum value. The box and whisker technique allows the central tendency and dispersion of data to be represented.

The 1D (T3) orebody was found to be the most morphologically complex, achieving an average compactness value of over 1200, whilst the other orebodies exhibit complexities of approximately 600 and below. The nose zone (T1) followed by 3Shear (T1) are the next most complex morphologically, at approximately 600 compactness index, whilst the 1C (T3) and 83 (Birchtree) orebodies are the least complex, achieving between 300 and 180 compactness indices. As a means of quantifying the complexity of each orebody the 95% confidence intervals about the means for each orebody were calculated. This provided an upper and lower limit of morphological complexity, within which range it could be anticipated that 95% of the orebodies would fall, see table 5.2.3.

[1] with the exception of the 1D orebody, which as a new orebody has only delineation drilling and mapping information.

Figure 5.2.1

Distribution of Morphological Complexity Index for the Thompson Orebodies

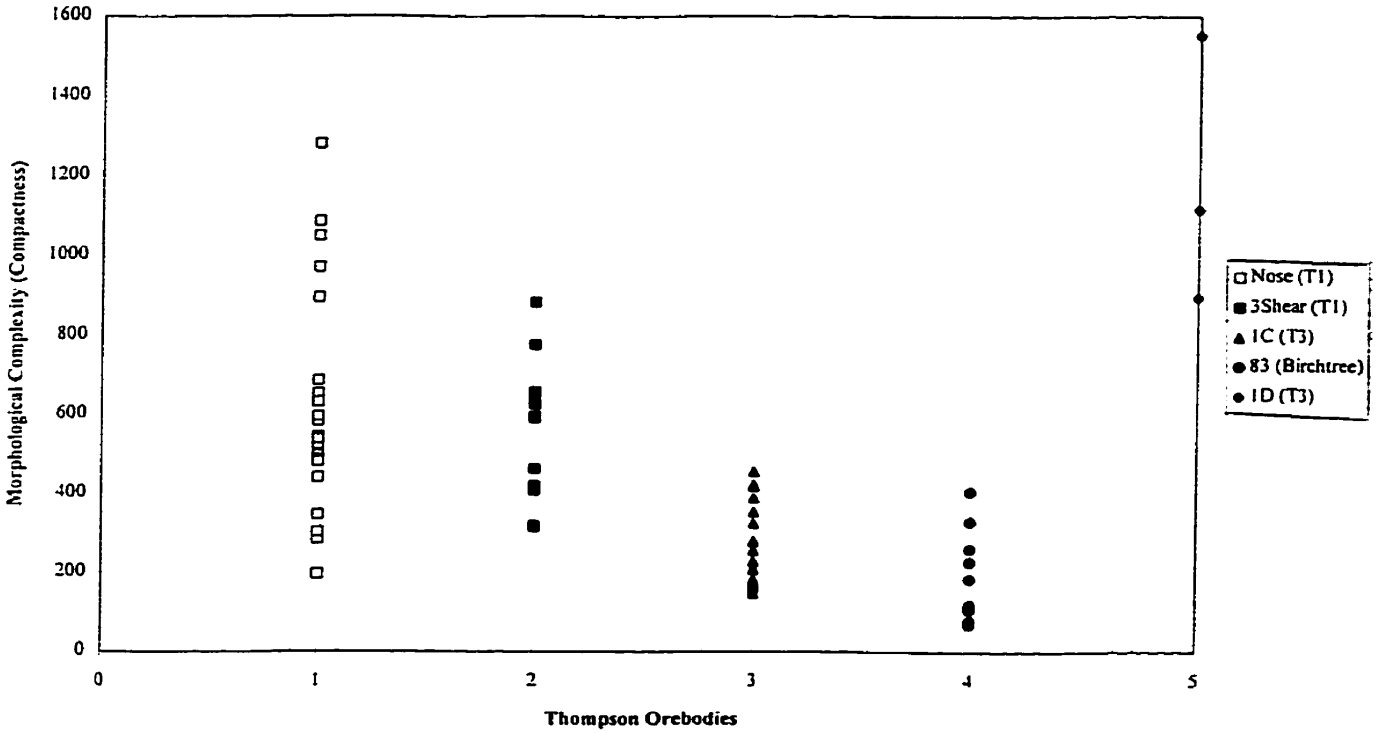


Figure 5.2.2.

Box and Whisker Diagrams for Thompson Orebodies

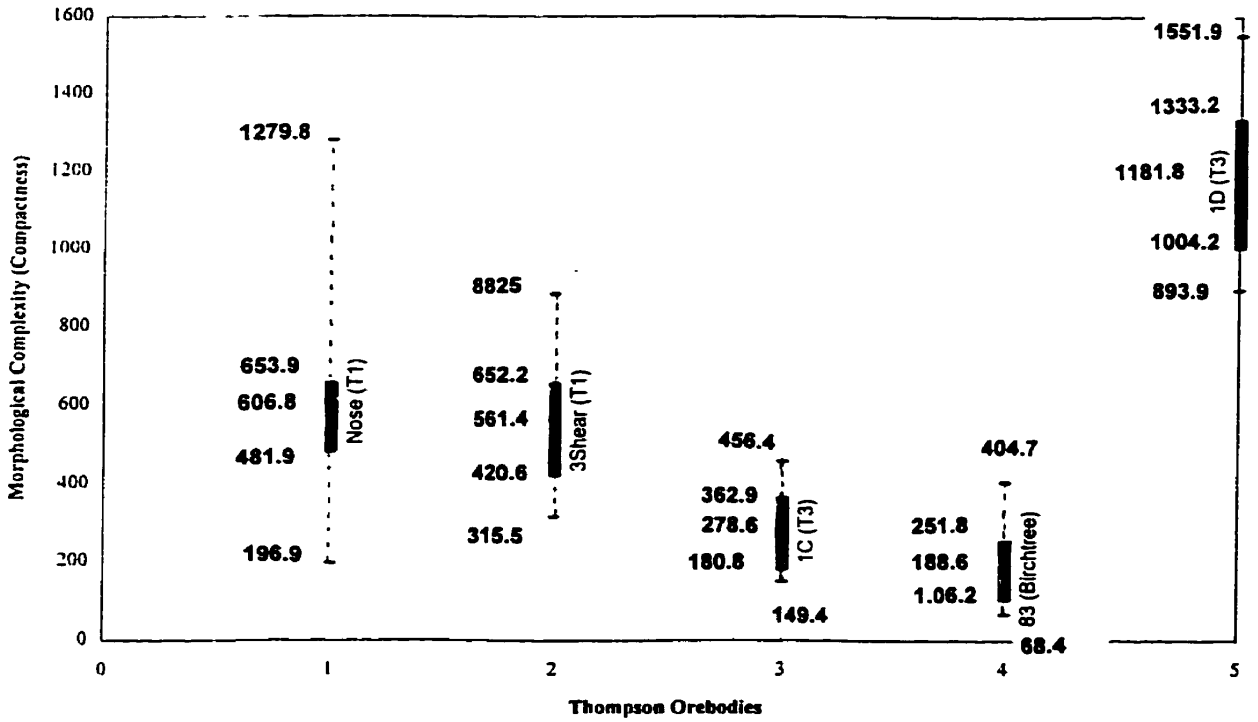


Table 5.2.3 Confidence Intervals for each Orebody Compactness

Orebody	Mean Compactness	Confidence Interval	Lower Limit	Upper Limit
Nose (T1)	606.8	102.9	503.94	709.7
3Shear (T1)	561.4	88.6	472.8	650.1
1C (T3)	278.6	49.4	229.2	328.01
83 (Birchtree)	188.62	67.2	121.5	255.83
1D (T3)	1186.8	309.44	877.35	1496.23

This approach allows us to identify with 95% confidence that the above ranges characterise each orebody. It can thus be seen that the 1D orebody is in a distinct class of compactness, with a range between 870 and 1500. However, both T1 orebodies have overlapping ranges between 500 and 650, with the Nose orebody having a higher upper limit (710) and the 3Shear orebody having a smaller lower limit (470). Similarly the 1C (T3) and 83 (Birchtree) orebodies have overlapping ranges between the 230 and 260, with 1C achieving a larger upper limit (330) and 83, a smaller lower limit (880).

The confidence limit, however, assumes a uniform data distribution yet, as the box and whisker diagrams show, all of the distributions for each orebody are slightly positive skewed. The few extreme measurements are thus distorting the midrange and mean towards the right tail. Thus we can expect that the midrange[2] exceeds the mean value. It can be interpreted from this that at least one section of an orebody will generally be more complex than indicated by the rest of the orebody. Exceptions therefore to the 95% confidence ranges presented above should be expected.

[2] Midrange is the average of the minimum and maximum values.

5.2.1 Discussion.

Based on the mine data the impact of structural form appears to have had a large effect on the morphological complexity of the orebodies. These effects are summarised in table 5.2.1.1.

An interesting point for further discussion is that the 1C and 83 orebodies which achieve similar low morphological complexities, are big producers of ore in the Manitoba Division, mined in panels as they are wide. Whilst the Nose and 3-Shear orebodies achieving similar high values are both long slender orebodies, producing lower amounts of ore. The extreme of 1D, being a thin stringer type deposit, appears to indicate that morphological complexity is related to width of the orebodies.

One factor that may be increasing the complexity of the 1D orebody is that it is defined only from delineation information and thus in comparison to the other orebodies it has a lower information density. However, as shown previously in Chapter 4, increased information often results in increased complexity. Thus it can be assumed that the complexity will increase in 1D as more drilling and mapping is undertaken and greater information retrieved.

It is also important to emphasise that the peridotite inclusions present in the Manitoba orebodies also influence the morphological complexity, but between the orebodies reviewed here, it appears to be less significant in controlling morphological complexity than the structural history. However, if geotechnical complexity were considered the influence of peridotite and the SUM inclusions would be of greater significance.

Figure 5.2.1.1 Summary of the impact of structure on complexity

Morphological Complexity (Compactness)	Orebody	General Morphological Characteristics	Geological Structure
880-1500	1D (T3)	Multiple bands of boudinaged ore, numerous interface patterns.	Severe tight isoclinal folding with upwards dilation of ore at the top of folds.
500-710	NOSE (T1)	Boudinaged orebodies (locally this is debatable); contorted such that a variation in dip (>180 degrees) of the orebodies occur.	Located on the nose of a fold, much dilation of the ore about the nose. Some peridotite present.
470-650	3SHEAR (T1)	Boudinaged orebody; less contorted than at the nose with second limbs occurring as a result of the shearing process.	Located on the limb of the major fold structure yet suffers from shear fractures, displacing ore, sliding one part of the rock past the adjacent part. Creates ill defined ore/waste contacts. Peridotite present.
230-330	1C (T3)	Boudinaged orebody; following one dip direction with well-defined contacts and little dilation of ore.	Located on the limb of a fold: the orebody suffers from shearing and faulting, but ore/waste contacts are easily defined. Few peridotite bodies present.
120-260	83 (Birchtree)	Boudinaged, steeply dipping orebody displaying little contortion.	Contains far less peridotite bodies than other orebodies at the Birchtree mine. Not a contorted orebody, suffering from little faulting.

5.3 The General Geology of the Sudbury Basin

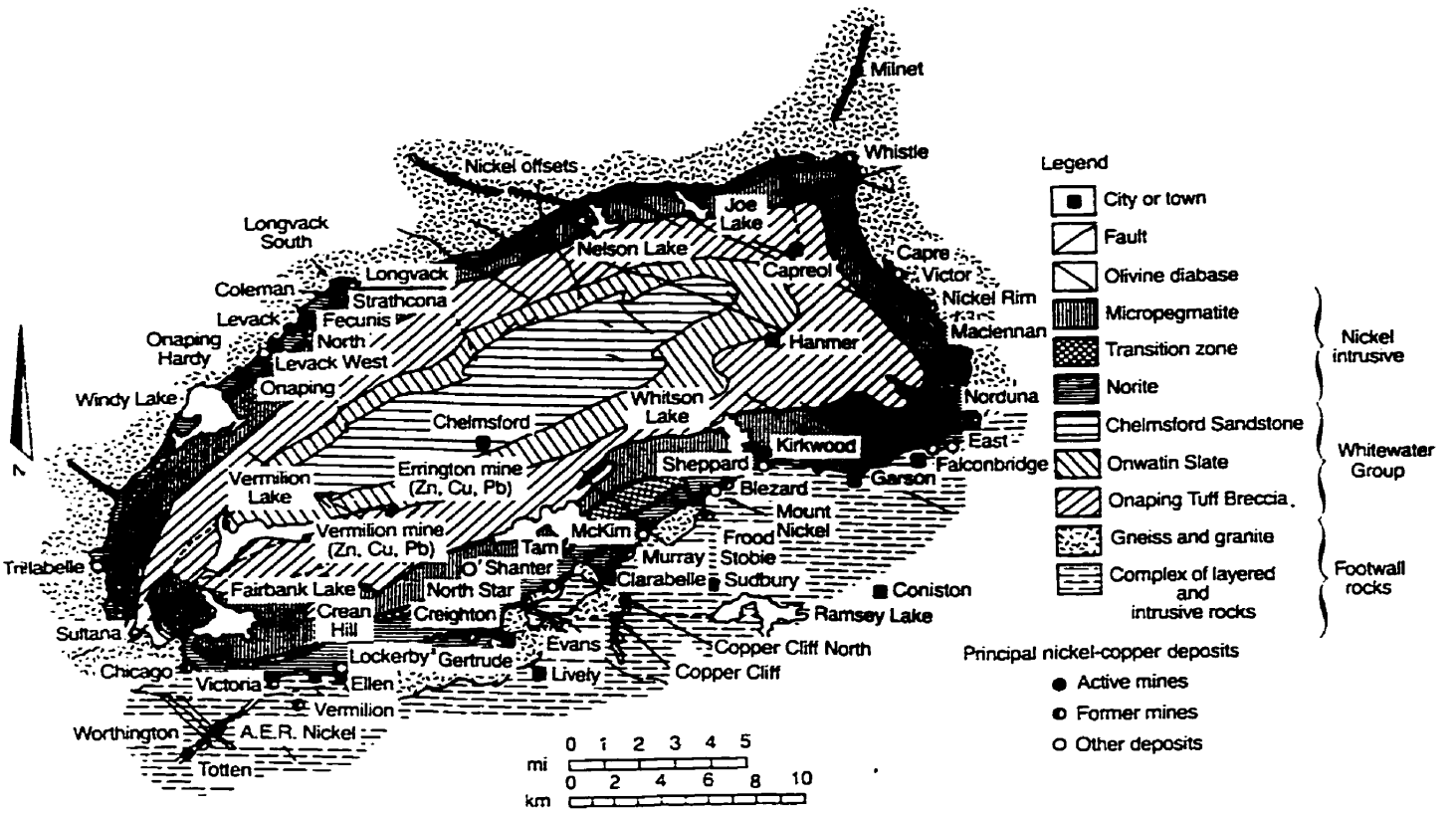
The Sudbury District, Ontario, has been one of the world's most productive nickel mining areas. It has yielded about 8 M tonnes of this metal, about the same amount of copper, and minor quantities of the platinum metals; cobalt, iron, sulphur, gold, silver, selenium and tellurium (Guilbert and Parks, 1986).

The mineralization origin has and still is controversial. Arguments for a genesis are based on either magmatic activity or meteorite impact with the Precambrian shield. The more commonly held belief is the latter.

The basin (as illustrated in Figure 5.3.1) is elliptical in form approximately 60 km long and 30 km wide, with a long axis trending east north-east. In cross-section, the complex in which the nickel irruptive (an intrusive suite of orebodies) lies is beneath the Whitewater Group sediments and above the older basement complex.

The nickel irruptive is composed of a lower sublayer, covered by norite and subsequently a micropegmatite. The copper-nickel ores are associated with this sublayer, particularly where the sublayer is in contact with the basement footwall rocks. The contact dips at approximately 41 degrees south in the north of the basin and at approximately 65 degrees north to the south of the basin.

Figure 5.3.1 Geology of the Sudbury Basin



5.3.1 The Ontario Division Mines

The sublayer itself is composed of two major variants, an igneous gabbro-norite-diorite[3] rock and a group of mafic felsic[4], generally leucocratic[5] breccias[6]. Both rock groups contain the Fe-Ni-Cu Sulphides. The sublayer is a gently dipping sheet with ore occurring as: irregular lenses along the floor of the complex; as smaller bodies in depressions or troughs in the complex floor called embayments[7]; and as steeply dipping to nearly vertical dike-like bodies called offsets, which project outward towards the footwall.

These orebody types were recognised in the 70's and are exemplified by the north Range - the South Range and the offsets, representing respectively the Normal footwall contacts, embayment and offset environment. Cross sections for this study of complexity were selected from each of these environments and are described below:

- Creighton Mine 400 orebody

  The Creighton mine orebodies represent the normal footwall environment and as such tend to resemble sheet-like orebodies, outlined to a depth of approximately 3 kilometres. At Creighton the orebodies dip downwards an unknown distance following the contact of the sulphides and sublayer rock. The contact is sharp against the older granite and gneiss, but upward against the norite contact the contact is obscure and poorly defined. Here sublayer material is cut out by a series of faults that run parallel to each other and are concentrated close to the contact.

---

[3] Gabbro - chiefly of plagioclase and pyroxene; Norite similar to Gabbro with higher plagioclase content; Diorite - a coarse grained plutonic rock, composed of plagioclase feldspar, hornblende, pyroxene and little or no quartz.

[4] mafic- rocks that contain an abundance of magnesium and iron-rich minerals e.g. olivine, pyroxene, amphibole, biotite etc.; felsic is the complement of mafic a lighter coloured rock it contains much feldspar and silica.

[5] leucocratic meaning fine grained

[6] breccia - a coarse grained clastic rock composed of broken, angular rock fragments, enclosed in a fine grained matrix.

[7] embayment - the incursion of a down warped region of stratified rocks into other rocks

Slices of the ore have been structurally inserted into the footwall rocks, well after the ore had crystallised. Large 'rolls' are recognised in the faults both along strip and downdip. In most places the faults lie close to the footwall and control the position of the ore. pieces of massive sulphide occur along the faults and in the brecciated footwall rock adjacent to the faults.

The ore can be massive, containing up to 95% sulphide, but the majority occurs in disseminated form within the silicate rock as: irregular grains in the gabbro-norite textural fabric; disseminated in schist-gneiss wallrock fragments; in sublayer gabbro which can contain some peridotite inclusions. Typically the ore achieves grades of 1% Cu and 1% Ni.

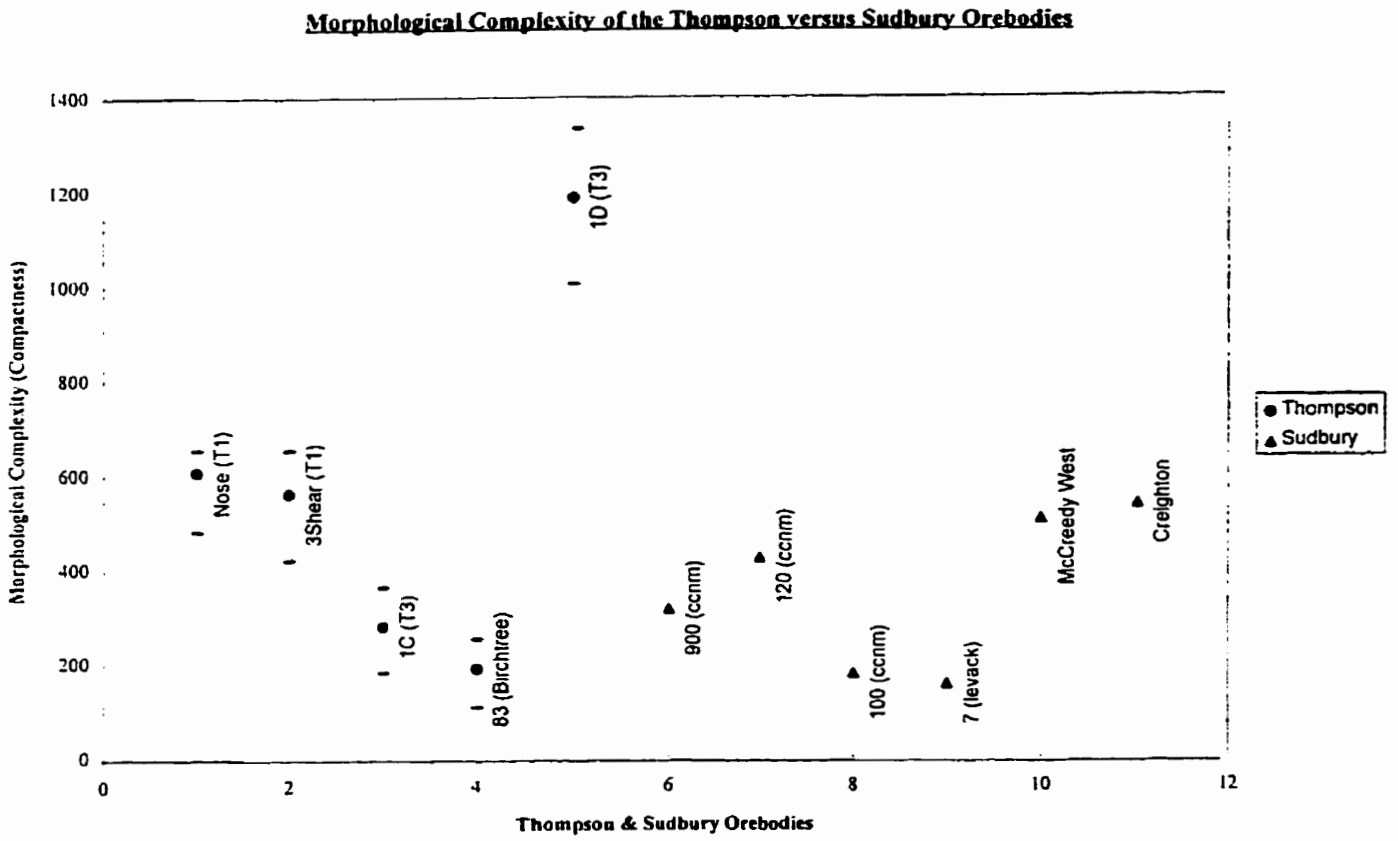
- McCreedy West & Levack Mine Orebodies

  Both represent the embayment environment, thus the orebodies tend to be smaller and lie in depressions and troughs, following the regional trend of the irruptive contact.
  The norite sublayer contains inclusions as well as sparse sulphide, which constitutes ore locally. The sulphide also occurs in the granitic breccia: as blebs in its matrix, which coalesce to form mineable pods; also in disseminated form. Massive sulphide can be found in the basement rock in a rounded to angular form. Peridotite inclusions are also present, posing ground control problems.

- Copper Cliff North Mine 900, 120 and 100 orebodies

  These orebodies reflect the offset environment. These mineralised dike-like bodies of quartz-diorite sublayer rock cut at low angles across the north-east trend of steeply dipping volcanic and sedimentary floor rocks. The economic sulphide concentrations are spatially associated with inclusion-rich quartz diorite with local thinning of the dike. Thus stringer type ore is present. Sulphide also occurs as massive bodies, within the breccia as blebs in the quartz diorite matrix, and within the low grade siliceous ore.

Figure 5.4.1


Morphological Complexity of the Thompson versus Sudbury Orebodies
Morphological Complexity (Compactness)
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
Thompson & Sudbury Orebodies
Nose (T1)
3Shear (T1)
1C (T3)
83 (Birchtree)
1D (T3)
900 (ccnm)
120 (ccnm)
100 (ccnm)
7 (levack)
McCreedy West
Creighton
Thompson
Sudbury

5.4 Ontario Mines Complexity Analysis

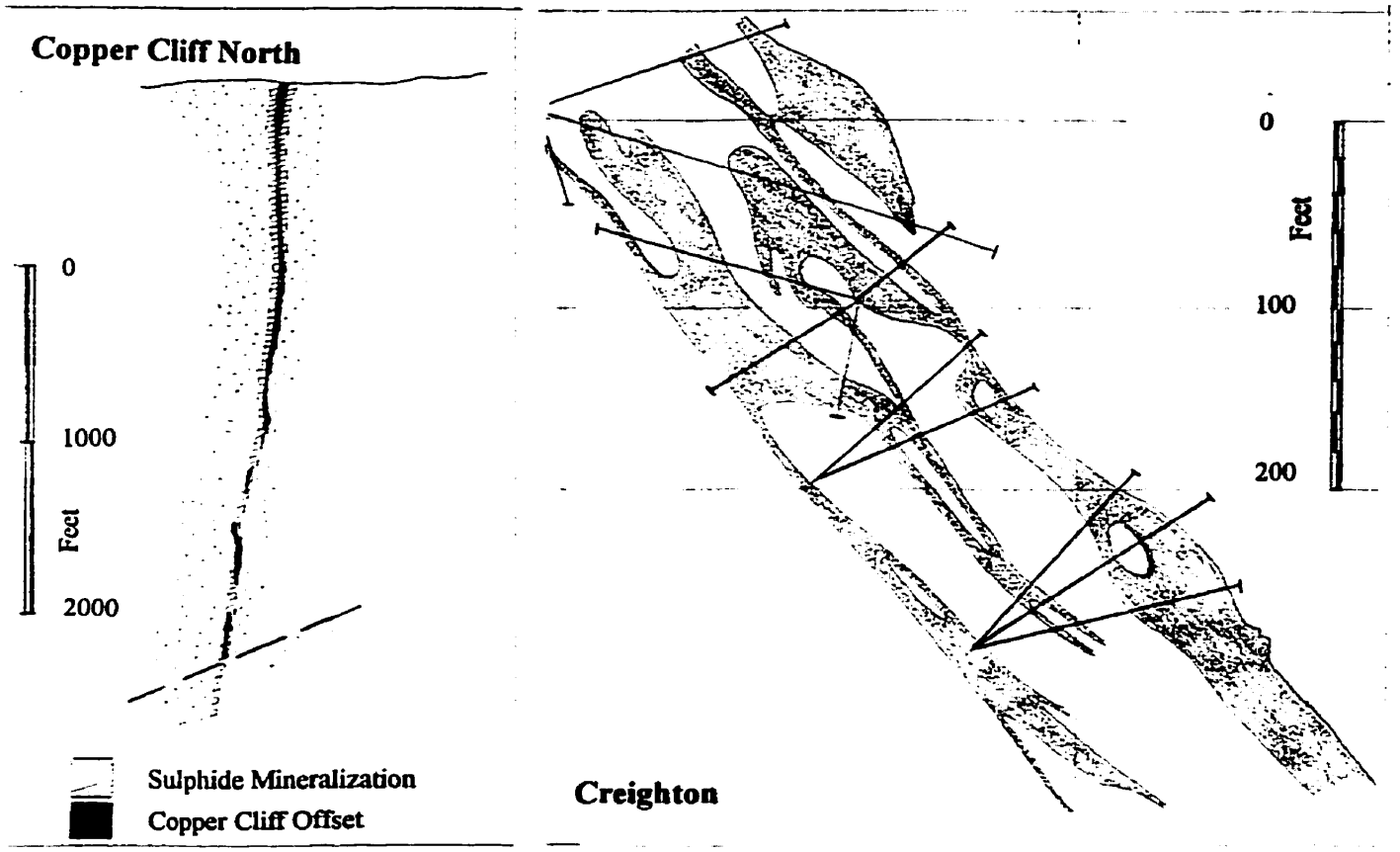
Representative sections were collected from the Ontario mines of Inco Limited. Unlike the Manitoba mines, ranges of expected values were not calculated for each orebody. The intention was merely to indicate how in general terms the morphological complexity of the Ontario orebodies compare to those of Manitoba. Figure 5.4.1 describes the results for Ontario orebodies comparing them to those for Manitoba.

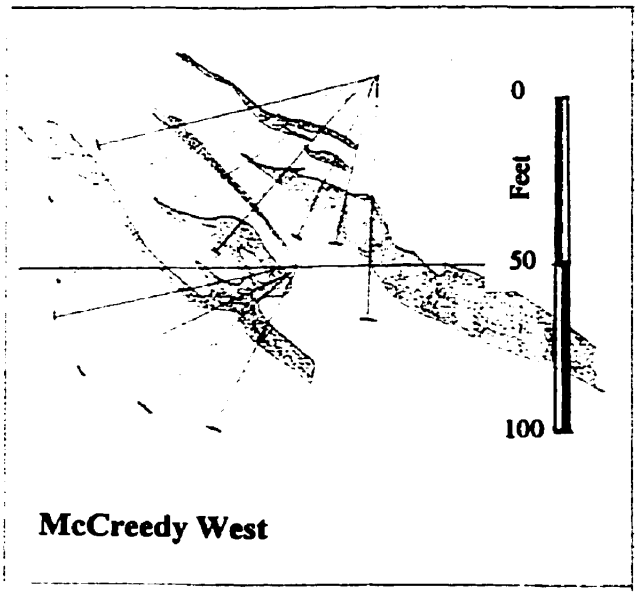
Significantly it can be seen that the range of indexes achieved are very similar to those achieved by all but the 1D orebody at Thompson, with a general range between 200 and 550. The representative section provided for the Creighton Mine produces the largest morphological complexity at a value of 540, whilst McCreedy West Mine achieves a similar index at approximately 500. Copper Cliff North Mine orebodies 900 and 120 are the next complex, achieving indexes of 320 and 420 respectively. The least complex orebody appears to be that of 7 orebody from the Levack mine, at a low 155 index.

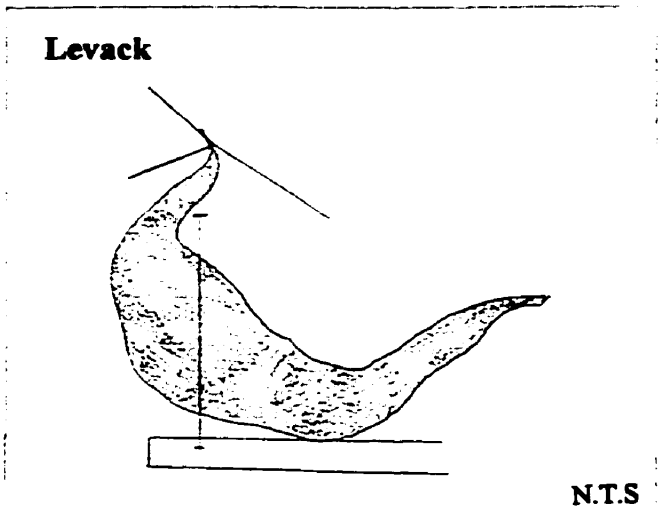
5.4.1 Discussion

It appears here that the morphological complexities in the Sudbury Complex are not distinguished by their environments. However, caution should be used in this conclusion, since little data was evaluated. The representativeness of the sections provided may be questionable, especially in view of the fact that until now there has been no means of quantifying the morphology of an orebody. Thus variations as indicated at Thompson of morphology across an orebody may well have been overlooked. The sections utilised from Sudbury are also less informative than those used for Thompson. This arises because they are not based on cut and fill stope mapping information but only delineation drilling and sill mapping. The likelihood is that had cut and fill information been available then the results found might have been very different.

Figure 5.4.1.1 Differences exhibited between Cross Sections representing different mines in the Ontario Division of Inco Limited







The advantage of applying this data to Sudbury is, however, that distinction is still clearly evident between orebodies, and when the orebodies are considered by eye the results shown appear to conform with visual interpretation.

Figure 5.4.1.1. illustrates the differences between each of the Ontario mine sections reviewed. Both the section provided for Creighton and McCreedy West mines are very similar, depicting a number of narrow ore veins dipping at 45°. The Copper Cliff North orebodies depict extremely steep orebodies, dipping at almost 90 degrees, with the 900 and 120 orebody being longer in length and narrower than the 100 orebody, but wider than the other orebodies depicted. It is felt that the narrowness of the orebodies for 900 and 120 results in the higher complexity than that achieved for 100 orebody. The Levack mine result is perhaps the most erroneous as it is based on four representative sections for the orebody, three of which are simple and one of which is very detailed. Owing to the greater information density for the latter it appears to be far more complex, achieving an index of almost 400. It is felt that this more complex section is probably a truer reflection of the orebody characteristics. If this is assumed then the complexity index resembles that of the McCreedy West mine index and can thus be explained by the fact that they both lie in the embayment environment.

On reflection it thus appears that the orebodies do lie in distinct morphological complexity ranges as determined by their geological environment, see table 5.4.1.2:

Figure 5.4.1.2. Morphological Complexity summarised for Sudbury Orebodies

Morphological Complexity (Compactness)	Example Orebody	General Morphological Characteristics	Geological Environment
540	Creighton	Numerous narrow veins dipping at approximately 45 °	Normal Footwall environment, obscure contact with norite. Cut by a number of faults, which displace the ore.
400-500	McCreedy West & Levack	Numerous narrow veins steeply dipping to 45 °. Orebodies are smaller than those of the normal footwall environment	Embayment environment, but lying in depressions and troughs the ore is less complex than that of the normal footwall, as the contacts tend to be more clearly defined.
170-430	Copper Cliff North	Steep dipping, dike like orebodies. More linear and far less limbs of ore than in the other environments	Reflect the offset environment.

5.5 Comparison of Morphological Complexity of Ontario and Manitoba Orebodies.

It can be seen from the analysis undertaken that complexity in terms of morphology is a real phenomena that as such can be quantified. The use of compactness as a means of determining an index for each morphology also appears to be appropriate.

Between Sudbury and Thompson, the influence of structure on the morphological complexity of an orebody was clearly exhibited. The sections from the Sudbury orebodies also illustrated that ore genesis affects its complexity, and in fact has a similar influence to structural history.

It is significant to note that similar complexity indexes for morphology were found for both Manitoba and Ontario Division mines, yet it is known that dilution is more problematic and critical at Thompson. This thus highlights that morphological complexity can not be treated in isolation. All other parameters influencing overall complexity should be considered, such as geotechnical complexity, in exerting control over dilution. On the other hand, this may indicate that should Manitoba Division improve their ground control such that dilution is further restricted, then the recoveries and selectivity as achieved in Ontario mines could be approached. Dilution is also controlled by the mining practice.

Mining practice relates to design and people and product quality. Design is a function of the MDPPC which provides the rationale for method selection and production control. People and Product quality refers to the competency and ability of the engineering and operation staff; product quality refers to the reliability of explosives and tools used in the operation.

CHAPTER 6 - MINING METHOD PERFORMANCE

6.0 Mining Method Performance and Complexity

From the previous chapter it has clearly been shown that morphological complexity is a real phenomena, but more importantly that it can be quantified. It is the intent of this final chapter to relate this ability to quantify complexity to its influence over mining method performance. This chapter outlines current methods utilised to measure mining method performance and focuses on how they can be integrated with a complexity index. The use of the morphological index to determine the most appropriate application of a mining method shall also be discussed, from the particular point of view of determining optimum stope height. This is the first time that this has been attempted. The ability to model morphological complexity, based on historical data, should prove to aid significantly the future application of mining methods and mine design.

6.1 Measurements of Mining Method Performance

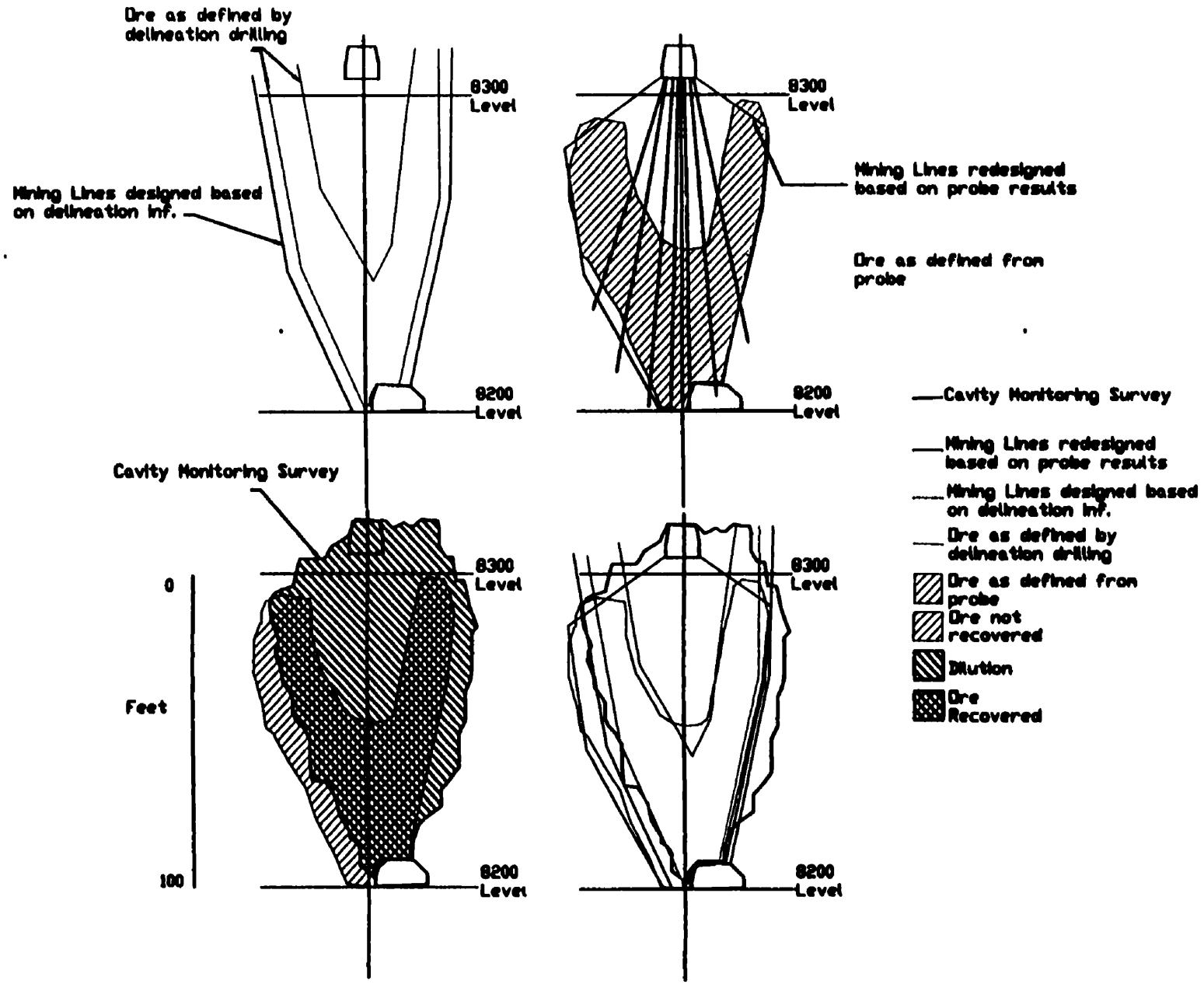
Mining method performance has historically been based on production rates, grade and tonnage, yet little work has been undertaken on measuring the efficiency of individual ore block production performances. Manitoba Division due to their problematic orebody complexity experience high mining costs. This is significant, especially in view of Inco's recent acquisition of the potentially low cost, high productivity mine at Voisey's Bay. In the past, Manitoba Division were also able to reduce their overall costs with the aid of an open pit operation which has now been exhausted. As a result, much emphasis has been placed on producing a system to measure mining method performance in order for areas of improvement to be identified, rather than as a means of apportioning blame (Pers. Comm. Sorenson, 1997).

The basis of the performance measure designed by Sorenson et al (1997) is to compare the geology as mapped (or probed) to the consequential mine design and then to the actual ore recovered (based on Cavity Monitoring Surveying technology - CMS, Pers. Comm. Mahony, 1997). Figure 6.1.1 illustrates the concept of this methodology. It describes three domains representing: the mineral outline, the stope design and the mineral recovered. It follows that for a truly successful operation the mineral outlined would match perfectly the stope design and that the mineral defined would be totally recovered, thus the circles would overlap. In reality, however, this ideal is not met and only portions of the mineral defined are designed within the stope and finally extracted.

In addition to these three circles, it is very significant for a geologist to compare a fourth circle, one which represents the mineral as defined prior to blasthole probing, i.e. based on geological mapping and delineation drilling only. In fact Inco's Ontario Mines Technical Services (MTS) have attempted this, although not employing this 'circle' methodology. As discussed previously in Chapter 2, through comparison of the ore enveloped, as defined from delineation drilling, to that defined after blasthole probing, MTS believe that a saving of at least $30 M over one year was realized.

Manitoba Mines Research Department employed their performance measures on 13 stope blocks from the Thompson (T1) mine, determining that the total tonnes of dilution suffered beyond design was 25,400 tonnes. 20% of the waste, from that tonnage blasted was separated and left in the stope muck pile, whilst the remaining 20,000 tonnes of dilution were sent to the mill. Through the processing of waste it is estimated that $30 per tonne is the direct cost of moving, hoisting and transporting nickel out to tailings, thus $600,000 was spent on treating dilution beyond that designed, considering only 13 blocks. An additional penalty occurs, howver, because whilst this 20,000 tonnes of dilution is treated, a further 20,000 tonnes of ore is not, and thus its production is displaced.

Figure 6.1.1 Cavity Monitoring Survey Examples - 108 Orebody Thompson, Inco Manitoba Division



With a revenue of $126 per tonne of ore (based on a nickel grade of 2.21%) the total loss in revenue is $6.5 M. If this logic is expanded to the rest of Manitoba Division's annual plan it equates to $37.9 M of lost revenue, breaking down into $8 M for the direct cost of treating dilution and $30 M for lost revenue because of displacement of ore, i.e. an opportunity cost.

These statistics are significant and the need for improvement is well justified. Yet in the areas of designed dilution (discrepancies between the mineral and design zones; dilution beyond design: discrepancies between design and actual zones) the geologist and engineers have the most control and potential to create significant improvement.

The second aspect of improvement in the dilution beyond design is currently limited. As stope designs are originally based on ore defined from delineation drilling, any redesign of the blast is restricted within this design, despite the fact that blasthole probe information may indicate that an entirely different design is more suitable.

A fourth dimension can be added, allowing the comparison of the mineral as defined from delineation drilling to that defined from blasthole probing. This should allow improvements based on further knowledge of ore complexity and the effect of information intensity. In the future as information technology and the digital mine concept comes into fruition, then so too will the ability to simulate orebody complexity within orebody models. This should create avenues for the mine engineers who plan stopes, to allow for complexity. Thus the agility of adapting mining methods to optimise recovery and selectivity should be improved. This combined with the 'just-in-time' information gained from blasthole probing should further reduce dilution beyond design and improve the recovery achieved.

A further advantage of employing a mining method performance measure as above, in conjunction with a complexity index, is that it provides for greater understanding. An example of this is that overall performance figures currently produced by Sorenson et al (1997) can be as low as 57%. To a production manager or general foreman this might motivate blame to be apportioned to the drill and the blast team, geologist and mine planner responsible for that stope. However, this percentage may merely be representative of the complexity of the orebody and not reflect the ability of those who worked on the stope. They may have undertaken the best work possible, designing and planning the stope operations to the best of their knowledge. Due to such orebody complexity, however, a 57% overall mining performance may be the best that could be achieved under the circumstances.

The remainder of this chapter considers the relationships between complexity and mining method performance with hindsight, utilising the concepts outlined above. It then attempts to use the complexity index as a means of determining mining parameters prior to development.

6.2 Complexity and the Manitoba Division MMP results

Members of the Inco Manitoba Division, Mines Research Department, as discussed above have undertaken the measurements required for the MMP measures they have devised on 13 blocks. In order to understand how the results of the MMP study relate to morphological complexity, the author has been provided with a limited amount of data for which the morphological complexity indexes and MMP values were calculated.

6.2.1 Methodology

The morphological index was measured as discussed previously in Chapter 4. However, the index was applied to the ore outline as defined from delineation drilling and to those determined after blasthole probing. Once the index was calculated for each section and the range of complexity considered for each block the results were compared to the MMP results. However, due to limited information, not all parameters were available to be calculated as required for the MMP indexes described previously. Thus adaptations have been made to these calculations to enable the use of the data available.

The parameters used were:

Delineation Performance:

The area of the blasthole probed ore outline that overlaps with that defined from diamond drill hole information, divided by the area of the geological orebody defined by diamond drill hole information.

Design Performance (utilising the blasthole probed information):

Area of probed ore outline that was included in the stope design (within the mining lines), divided by the total area of the orebody defined by probing.

Design Performance (utilising the delineation drillhole information):

Area of delineated ore outline, that was included in the stope design, divided by the total area of the orebody defined by delineation drilling.

6.2.2 Results

Table 6.2.2.1

Measured performance parameters obtainable for 50.5 Stope from the "A" zone of the Thompson 1D Orebody			
Section	Delineation Performance	Design Performance (using blasthole probed geology)	Design Performance (using delineation information)
g	0.73	0.68	1.00
h	0.65	0.62	1.00
i	0.70	0.81	1.00
j	0.94	0.98	1.00
k	0.84	0.87	1.00
l	0.82	0.93	1.00
Average (%)	78	82	100

Table 6.2.2.1 provides the performance measures for the data available for the Thompson 1D orebody. In this case the geological interpretation from delineation diamond drilling has been compared to that from probed information and to the stope design. This has produced three measures:

1. Delineation Performance - how closely the delineated orebody outline from diamond drill hole information matches that of the blasthole probed geological outline
2. Design Performance (using the blasthole probed data) - how closely the mining lines match the blasthole probed geological outline.
3. Design Performance (using the delineation data) - how closely the mining lines match the delineated geological outline from diamond drill hole information.

Unfortunately no CMS data was available to allow the overall and actual performance parameters to be calculated.

Were this information available it would provide the geologist or engineer with a means of quantifying how well geological interpretation met with stope design lines and the overall recovery (the cavity which remains after mucking).

The data for the 1D orebody indicates that in this stope block the delineation performance is wide ranging between 95% and 64% accurate, with an average of 78%. This good accuracy in delineation is reflected in the fact that even after blasthole probing and redefining of the mining lines the initial geological interpretation still lies totally within these mining lines, represented by the 100% performance achieved for design performance (using the delineation data). Interestingly the blasthole probing proved of little assistance, since the mining lines could not be adjusted and all of the ore defined in this manner could not be recovered. This is reflected in the lower average design performance achieved when using blasthole probing of 82%.

A further analysis was undertaken which considered the influence of information density on the stope morphological complexity. Table 6.2.2.2 contains the results.

Table 6.2.2.2

Measured morphological complexity indexes obtained for 50.5 Stope from the "A" zone of the Thompson 1D Orebody		
Section	Complexity of stope section (from delineation diamond drill hole information)	Complexity of stope section (from blasthole probing information)
g	57.8	62.2
h	45.1	66.4
i	46.7	59.1
j	41.7	34.3
k	37.6	40.8
l	35.8	37.5
Average	44.2	50.1

The increase in data with blasthole probing, as expected, provides more definition and detail to the orebody outline and also increases its complexity from an average of 44 to 50. Although this difference is not very significant, for an orebody whose delineation performance was not as successful as in this case, the increase in complexity would be expected to be much higher. Table 6.2.2.3 provides the results for the MMP analysis undertaken on the Birchtree 108 Orebody for stope block 1040.

In this example it can be seen that the interpretation of the geological outline from delineation drilling was not as successful as in the previous case, with an average of only 55% performance being achieved. However, the average is, as the range of values achieved for each section show dramatic ranges in performance from 18% to 79%.

Table 6.2.2.3

Measured performance parameters obtainable for 1040 Stope from the Birchtree 108 Orebody			
Section	Delineation Performance	Design Performance (using blasthole probed geology)	Design Performance (using delineation information)
a	0.18	1.00	0.27
b	0.27	1.00	0.71
d	0.79	0.95	0.80
f	0.53	0.95	0.76
g	0.70	1.00	1.00
h	0.68	0.98	1.00
i	0.71	1.00	1.00
Average (%)	55	98	79

In particular there are two sections through this orebody which were delineated particularly poorly when compared to the blasthole probing information,. These two results bias the average in a negative manner. The design performance, however, (using the blasthole robed data) is excellent at 98%. It is felt that this can be explained by referring to the morphological complexity values achieved for this stope (see Table 6.2.2.4).

As the table highlights, the complexity of this particular stope block is low, approximately 33 after probing, thus the design of a stope around such a simple morphological outline was straightforward. The design, therefore, was able to contain almost all of the defined ore, (from blasthole probing), achieving a design performance of 98%. As the initial delineation from diamond drill hole information, however, had produced an orebody with a higher morphological complexity of 65, the design performance (utilising this diamond drill information) is lower at 79%.

Table 6.2.2.4

Measured Morphological Complexity Indexes obtained for 1040 Stope from the Birchtree 108 Orebody		
Section	Complexity of stope section (from delineation diamond drill hole information)	Complexity of stope section (from blasthole probing information)
a	70	33
b	73	53
d	61	41
f	60	28
g	62	53
h	61	41
i	65	33
Average	65	40

6.2.3 Discussion

Limited analysis was undertaken on relating morphological complexity to performance parameters, due to the availability of information. However for the two scenarios presented the link between morphological complexity and mining method performance to the stage of stope design appears to be sensible and realistic.

Between the Thompson 1D , 50.5 stope block, and the Birchtree 108, 1040 stope block, a high design performance (98%) was indicated for the Birchtree stope block, which had a lower morphological complexity of 33. On the other hand, the more complex stope block with an average morphological complexity of 50, achieved a lower design performance of 82%.

This analysis provided further evidence of the information density effect on assessing morphological complexity. An increase in complexity was evident in comparing the low intensity technique of delineation drilling to the more intense information generated by blasthole probing. It is considered that this initial study provides evidence to support the continued research into the link between mining method performance and morphological complexity.

6.3 Utilisation of Complexity to define optimum stope heights

The previous work considered whether low MMP's corresponded to high morphological complexities, and general orebody complexity. As there is a distinct relationship that appears to relate complexity and MMP, it would seem a natural progression to integrate the complexity index of an orebody into the design of the mining method employed.

Although it has been implied previously that the simulation of orebody models with various complexities based on historical data, or data from similar environments, could allow the most agile mining methods for that orebody type to be chosen, a further clear example of this is seen by studying the relationship between complexity and optimum stope height. The tabulated data associated with this study can be found in Appendix I.

6.3.1 Methodology

By selecting at random a range of cross sections from throughout the Thompson orebodies, used previously in Chapter 5, the effect of stope height on complexity was studied. Four sections were selected from each orebody at random, but these generally represented four stages through the orebody.

As with the study undertaken on complexity of orebodies in Chapter 5, the morphology of the orebody was measured using Compactness for individual stopes within each orebody. The stopes were measured based on heights of 15m (50 ft), 30m (100 ft), 45m (150 ft) and 60m (200 ft). Figure 6.3.1.1 more clearly illustrates this methodology. The results were then considered for each section and orebody.

6.3.2 Results

Graphs were compiled for each section comparing complexity with the distance from the base of the cross-section. This was undertaken for 15m (50 ft), 30m (100 ft), 45m (150 ft) and 60m (200 ft) stope heights. Three types of analysis were undertaken, as follows:

1. 3-Dimensional comparison of complexity for 15 metre stope heights versus the elevation. This was undertaken for each orebody and the graphs are presented in figures (6.3.2.1, to 6.3.2.5).
2. Comparison of the different complexities achieved for each section for each stope height. (Complexity versus the distance from the base of the cross-section).
3. Comparison of complexity versus stope height for each section.

Analysis 1.

This analysis allowed for an insight into the 3-dimensional morphological complexity of each orebody. Using the 15 m stope height complexity values the most detailed representation of complexity throughout the orebody could be described. As it is expected that an orebody should, in general, describe similar morphological characteristics in section, this analysis also allowed the measure to be tested. Should unexplainable differences in complexity be measured between sections, which appear to describe a similar morphology, then the appropriateness of compactness as a measure of morphological complexity could be re-evaluated.

Using this analysis technique the following characteristics were determined:

Thompson (T1) NOSE Orebody (Figure 6.3.2.1)

- the base of the orebody is the most complex region.
- this complex base moves higher in elevation in a northerly direction in the orebody, thus indicating a southerly plunge to the orebody.
- the maximum complexity achieved is approximately 250.
- although variation between the maximum complexity of each section is evident, ranging from 100 to 250, the general form of the complexity versus elevation curve is similar.

Thompson (T1) NOSE Orebody, Complexity of 50ft Sections, s935,950,995,1015

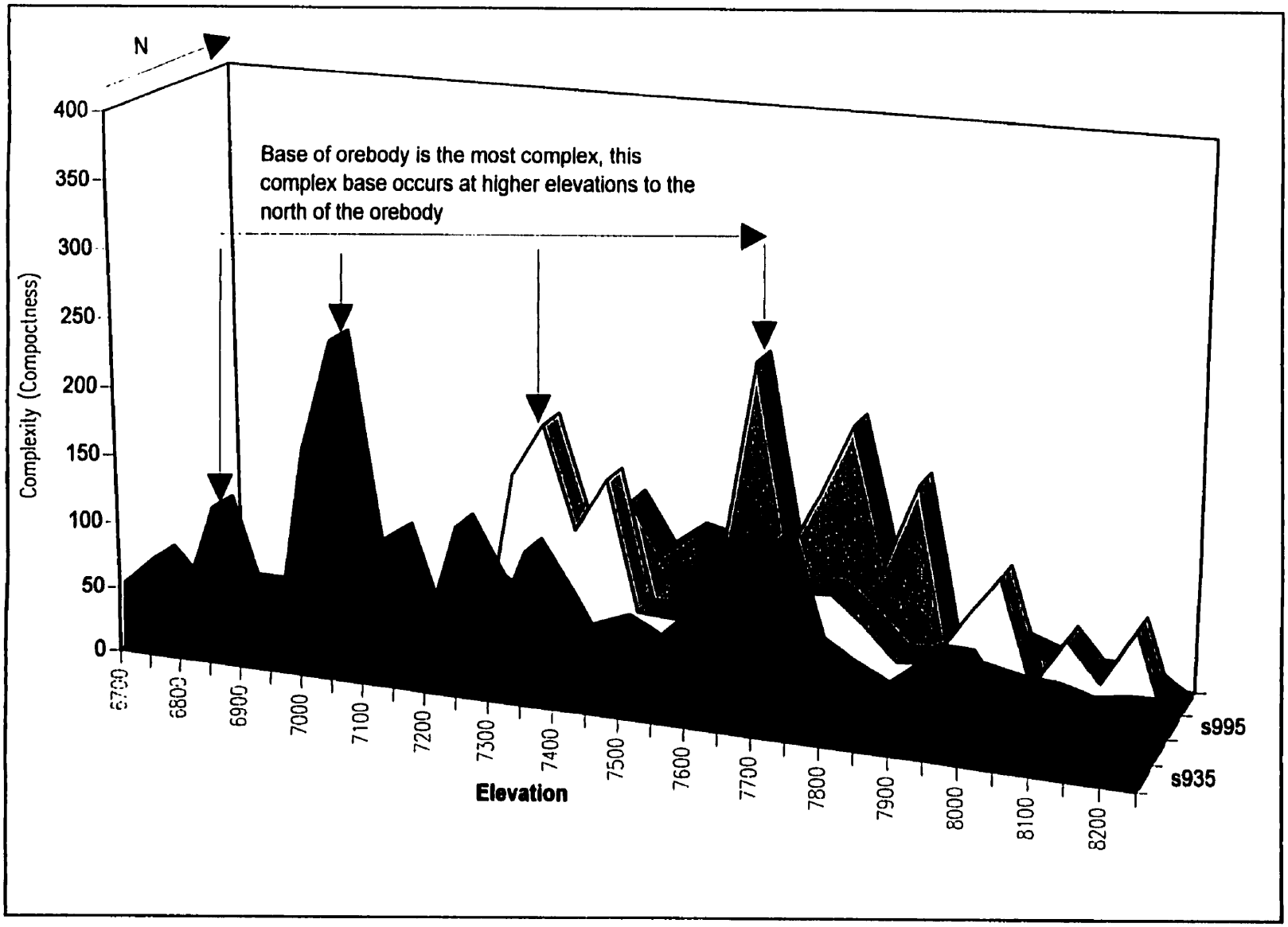


Figure 6.3.2.1

Thompson (T1) 3SHEAR Orebody, Complexity of 50ft Sections for Sections s845,860,875 and 900

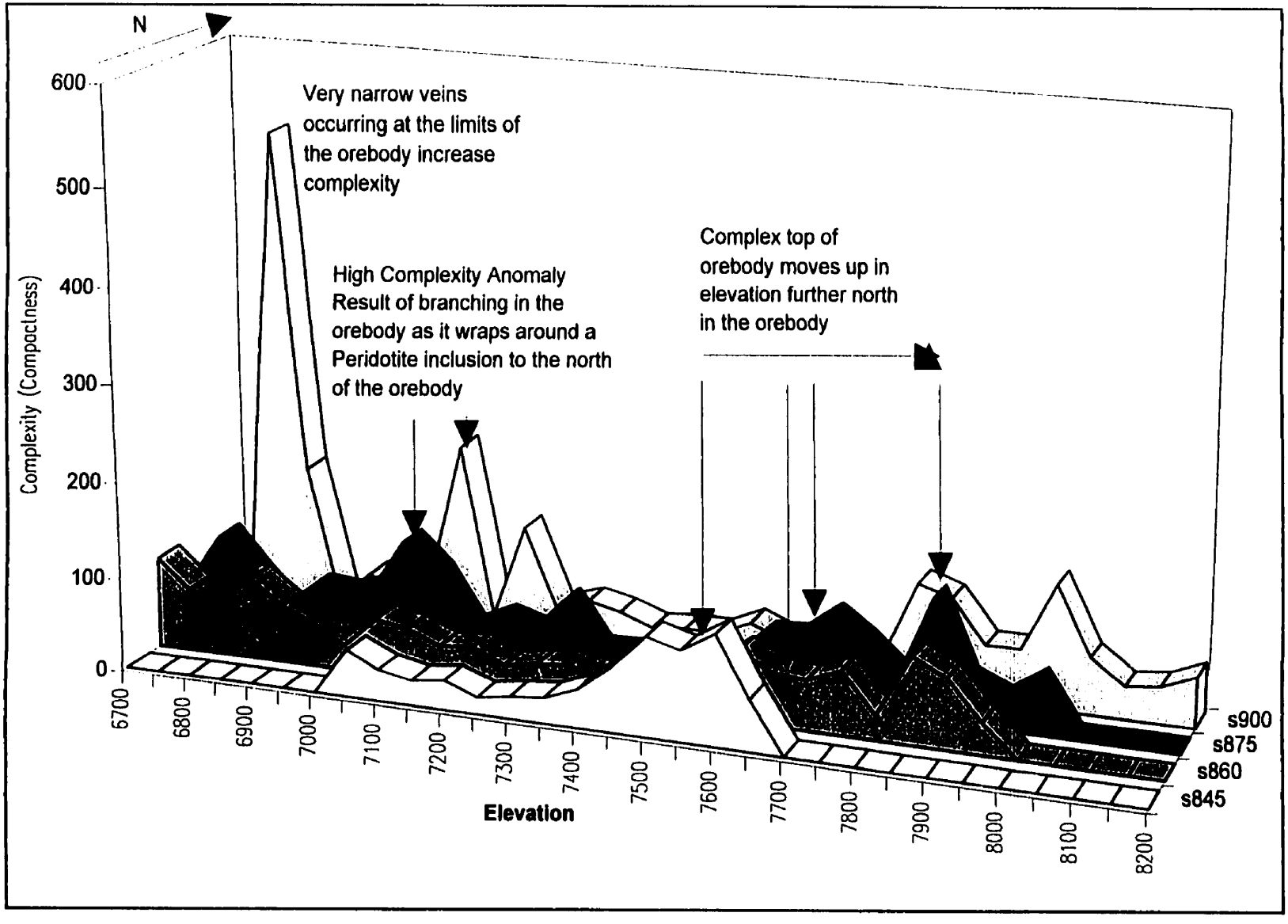
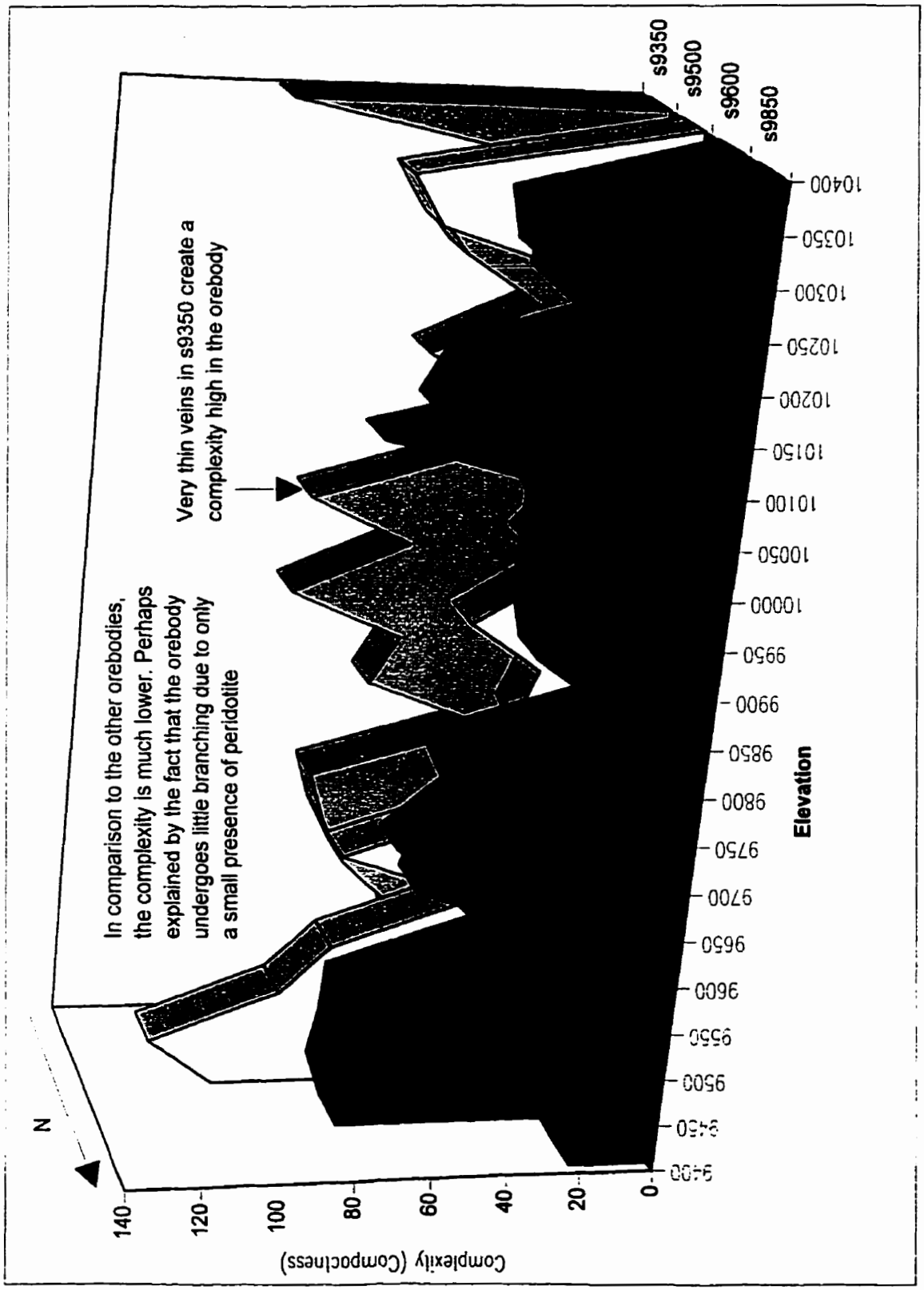


Figure 6.3.2.2

Figure 6.3.2.3


Birchtree 83 Orebody, Complexity of 50ft Sections, s9350,9500,9600 and 9850
In comparison to the other orebodies, the complexity is much lower. Perhaps explained by the fact that the orebody undergoes little branching due to only a small presence of peridolite
Very thin veins in s9350 create a complexity high in the orebody
N
Complexity (Compactness)
0
20
40
60
80
100
120
140
Elevation
9400
9450
9500
9550
9600
9650
9700
9750
9800
9850
9900
9950
10000
10050
10100
10150
10200
10250
10300
10350
10400
s9350
s9500
s9600
s9850

Thompson (T3) 1C Orebody - s32250,32550,32650 and 32950

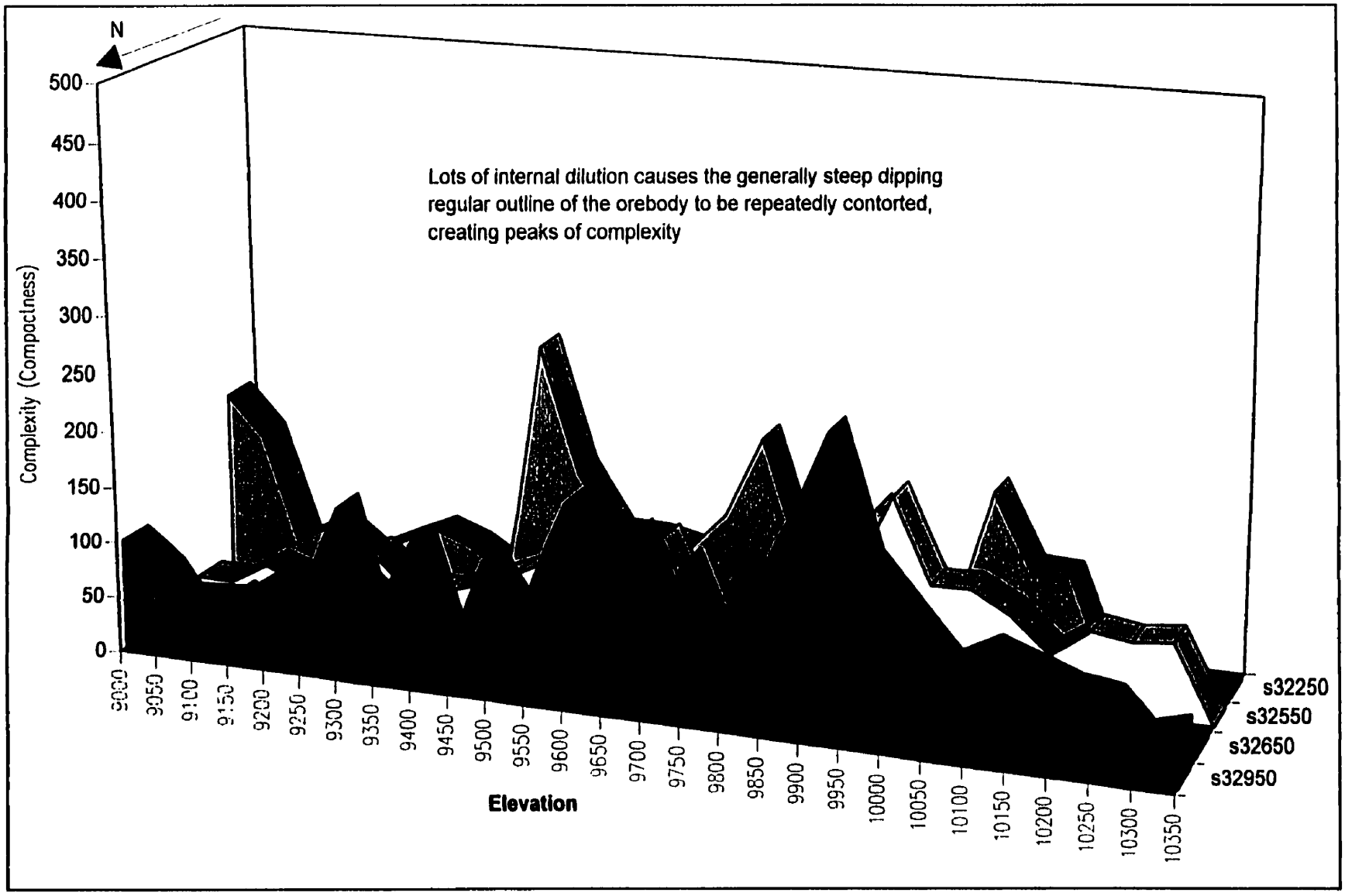
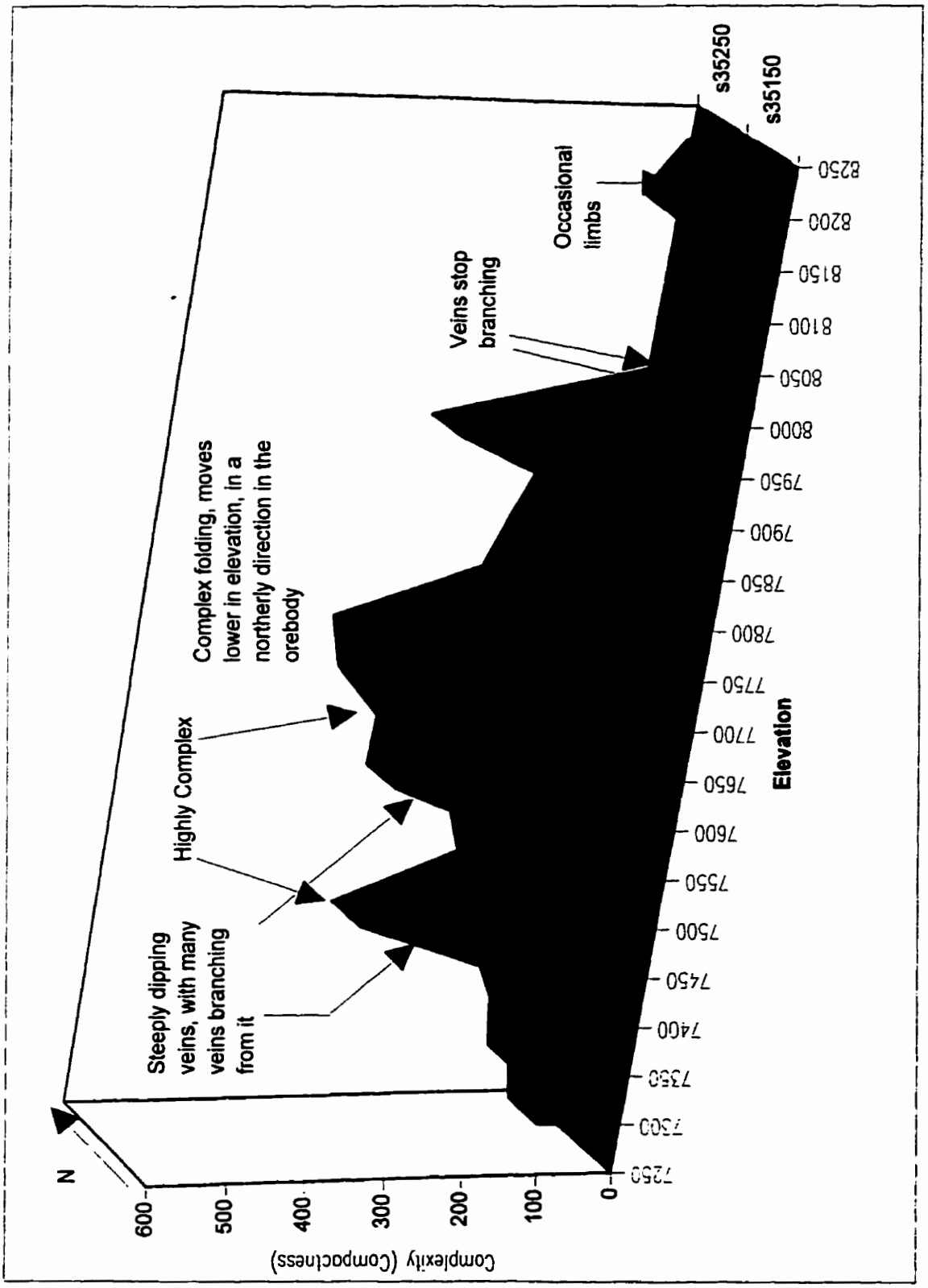


Figure 6.3.2.4

Figure 6.3.2.5


Thompson (T3) 1D Orebody, Complexity of 50ft Sections, s35150 and 35250
Complexity (Compactness)
0
100
200
300
400
500
600
N
Steeply dipping veins, with many veins branching from it
Highly Complex
Complex folding, moves lower in elevation, in a northerly direction in the orebody
Veins stop branching
Occasional limbs
s35250
s35150
Elevation
7250
7300
7350
7400
7450
7500
7550
7600
7650
7700
7750
7800
7850
7900
7950
8000
8050
8100
8150
8200
8250

Thompson (T1) 3SHEAR Orebody (Figure 6.3.2.2)

- generally low in complexity (100 or less), high complexity anomalies are evident.
- when correlated to the AutoCad™ sections the anomalies appear to accompany orebody branching. This orebody branching occurs as a result of the ore being contorted as it wraps itself around peridotite inclusions. This is more evident to the north of the orebody, where the inclusions are located.
- a trend of higher complexity is exhibited at the top of the orebody and this appears to move up in elevation in a northerly direction in the orebody, thus indicating a southerly dip to the orebody.
- extreme high anomalies are exhibited at the exterior of the orebody. It is felt that this is a result of the orebody pinching out, creating the appearance of a narrow veins in section and thus achieving a high compactness value.

Birchtree 83 Orebody (Figure 6.3.2.3)

- low in complexity, between 20 and 80. This is felt to be due to the low presence of peridotite, and thus little branching and contortion of the orebody.
- no extreme anomalies are evident. Where slightly higher than the average complexity is exhibited, it corresponds to slight thinning of the orebody and thus higher compactness values.

Thompson (T3) 1C Orebody (Figure 6.3.2.4)

- maximum complexity achieved is approximately 300, although certain sections only achieve a maximum of 150.
- a base complexity of between 50 and 100 is interrupted by peaks of complexity. This can be explained by the effect of internal dilution which causes the generally steep dipping regular orebody outline, to be repeatedly contorted and the complexity increases.

Thompson (T3) 1D Orebody (Figure 6.3.2.5)

- achieves the largest complexity, 400, of any of the orebodies measured
- at the foot of the orebody the complexity is greatest and decreases very rapidly with a decrease in elevation. It is the presence of steeply dipping and branching veins in this region of the orebody which increases its complexity.
- towards the top of the orebody the complexity decreases gradually, with peaks of complexity occurring where occasional branching limbs are reached.

Analysis 2

The comparison of the complexity measured for stope heights of 15, 30, 45, and 60 metre intervals for each section allowed for the effect on complexity of stope height to be adequately reviewed.

As is expected the most detailed description of complexity variance for each section was achieved with the 15m stope height. This is as a direct function of the amount of data points provided and that each data point represents a small percentage of the orebody. Thus a distinct smoothing effect was evident for the lines representing increasingly larger stope heights. Figure 6.3.2.6, represents the data for the Thompson (T1) NOSE Orebody and for each section it can clearly be seen that the 15 metre lie describes more fluctuations in the complexity than the 60 metre line. As this figure describes (the figures for the other orebodies are located in Appendix II), in general it can be seen that the increase in stope height results in an increased complexity. However, for certain points, as indicated by #1, #2, #3 on the figure, this rule is not always true. As can be seen occasionally the line for the larger stope height falls below the complexities achieved by a smaller stope height. This is due primarily to the smoothing effect but is also influenced by the information density changes which occur with the placement of different stope sill intervals. Figure 6.3.2.7 describes this phenomenon more clearly. It can be seen in figure a). That a stope sill spacing of 60 m provides detailed geological information from the sill and the estimated ore boundaries between the sills based on delineation drilling.

Figure 6.3.2.6 Complexity versus Distance from base of cross section for stope height intervals of 15 m, 30 m, 45 m and 60m for Thompson (T1) NOSE Orebody.

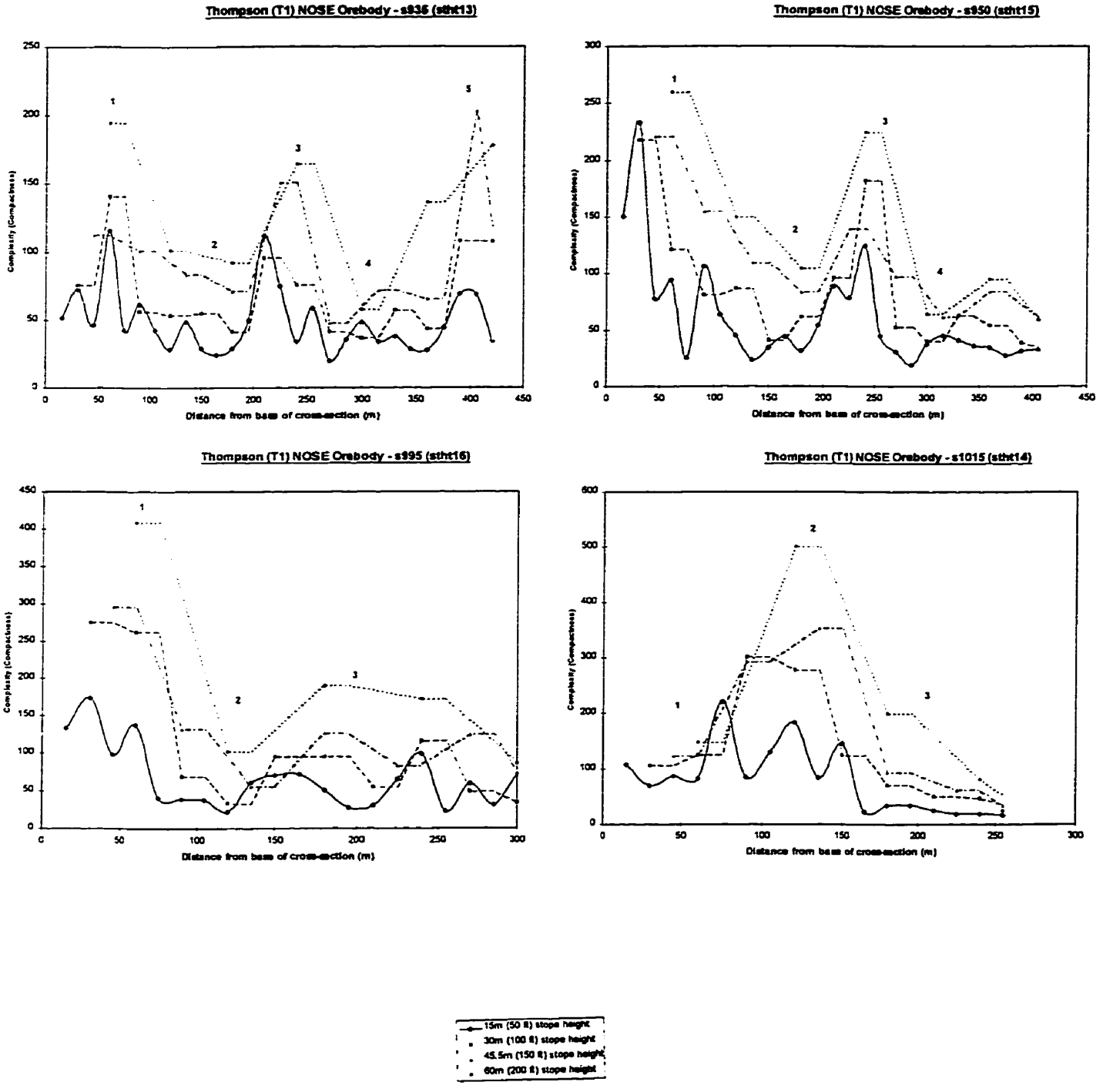
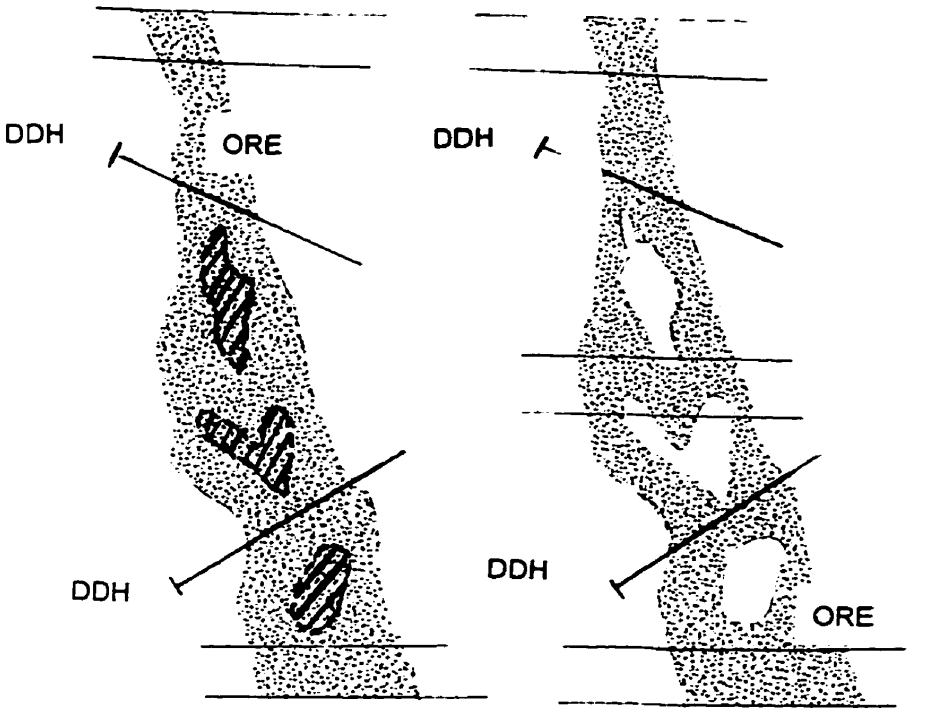


Figure 6.3.2.7 Effect of stope sill spacing on geological information



No information allowing the estimation for inclusions to be made

Ability to detect more information, such as inclusions, with low stope height

However, for a stope sill spacing of 45 m, the geological mapping information gained from the sill provides information relating to an inclusion within the orebody. Thus the geologist is able to allow for this in the complexity calculation, whereas with the 60 m interval this information was not provided. Thus despite the orebody being the same in each case, the interval of stope height provides different information in each case. With reduced spacing then more information is often provided. The orebody morphology can appear to be more complex, purely as a result of this effect.

Analysis 3

Comparison of complexity versus the stope height directly was designed to establish a trend which would indicate if complexity increased with stope height in a mathematical relationship. However, as figure 6.3.2.8 for the Thompson (T1) NOSE zone demonstrates (figures for the other orebodies can be found in Appendix III), although a positive linear trend is depicted for the relationship of complexity versus stope height, the significance of this trend line is questionable. The correlation coefficients achieved are low, less than 0.2 and thus it would not be justified to use the trendlines produced for each section as a means of qualifying the relationship. As the previous analysis showed, there is a relationship between complexity and stope height and one can assume that as stope height increases, then in general so too does the associated morphological complexity. One reason why this relationship is not clearly shown with this third analysis is due to the lack of any clear difference between the complexity values of each separate stope height, and secondly because for each stope height a large range of complexities can be achieved. Figure 6.3.2.9 illustrates this latter effect. Diagram a). describes a situation similar to that faced with the complexity issue, where the curves for each series are displaced, but the range of complexity values for each curve overlap. For this situation a low correlation coefficient is achieved, despite the fact that there is a relationship between x and y. In case b). however the linear relationship is significant using the correlation coefficient, since the ranges for each curve are totally separate.

Figure 6.2.8.3 Complexity versus Stope Height for Thompson (T1) NOSE Orebody

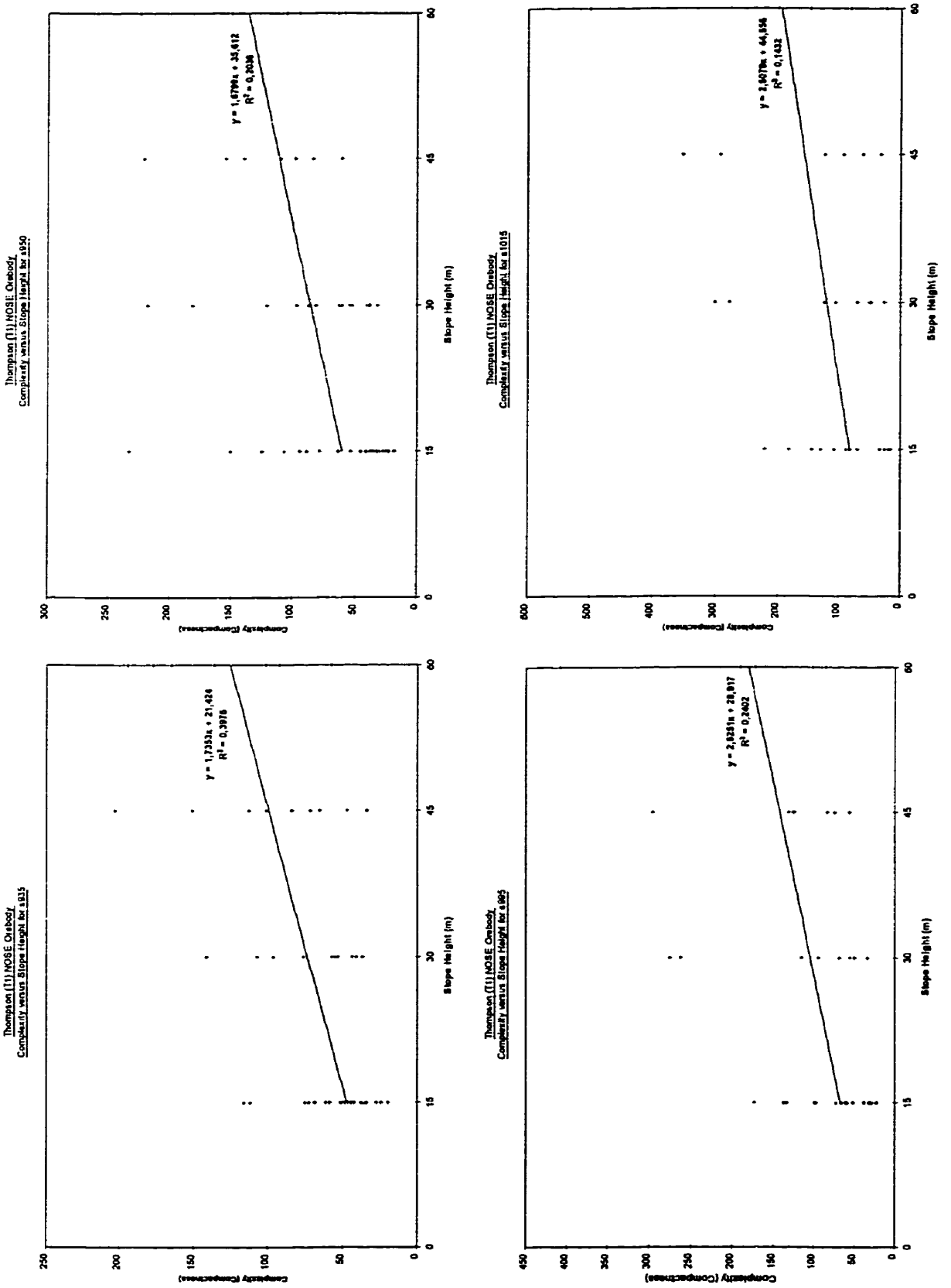
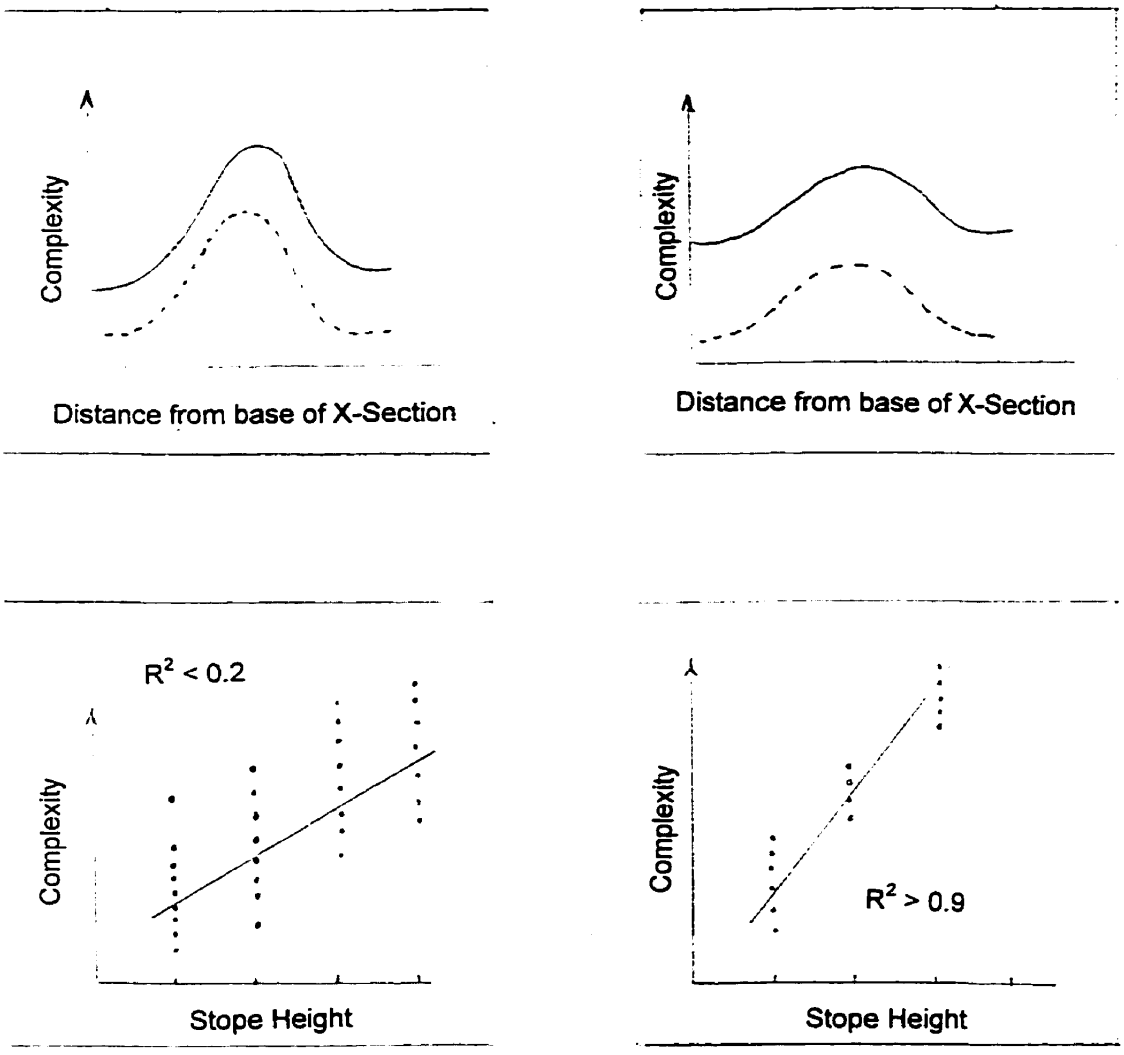


Figure 6.2.9.3 Complexity versus Distance from base of cross section-the problem with determining a linear relationship.



6.3.3 Discussion

From the stope height and complexity analysis it is evident that as stope height is increased then the associated morphological complexity of the orebody within that interval also increases. However, due to the large ranges in complexity exhibited in each section, a significant linear relationship is not evident. Polynomial relationships were also evaluated, but these also resulted in poor correlation. The analysis is therefore at the point where a relationship between stope height and complexity has been indicated, but no means has yet been determined from which optimum stope heights could be found directly.

If the link between mining method performance and morphological complexity is taken a step further, determining a level of mining method performance that needed to be exceeded, one could apply this to the determination of stope height. For a particular orebody complexity, one could anticipate certain morphological complexities to be faced for particular stope heights. Thus from the research undertaken in the beginning of this chapter one could estimate the likely MMP that would be achieved and alter the stope height until the MMP was acceptable.

CHAPTER 7.0 - CONCLUSIONS

The basis of the thesis was to quantify the complexity of orebodies within the base metal mines of Inco Limited's Manitoba Division, motivated by the need to maximise geological control. An element of concern in the lack of control in contemporary bulk mining operations. This merits resolution prior to any the initiation of mine design for future automated mining.

The work undertaken focused primarily on tactical geologic control in terms of determining the relationship between orebody complexity and mining method performance. Thus orebody complexity could be integrated into MDPPC aiding in the interpretation of data and the associated decision making process.

It is felt that the thesis has clearly demonstrated the problems and importance of quantifying complexity. Through the application of the measurement of compactness for orebody sections, it is possible to relate orebody complexity to geology. The use of Inco Limited Manitoba Division orebody data lead to the understanding of how structural elements effect morphological complexity. Whilst Inco Limited Ontario Division data provided evidence that the genesis of orebodies also leads to variances in morphological complexity.

An attempt was made to relate morphological complexity to mining method performance, by combining the complexity index with mining method performance parameters. Complexity was also used as a basis for determining stope design parameters. Analysis indicated that there was a relationship between the morphological complexity of an orebody and the stope design performance that was consequently achieved. It is concluded that further research into this relationship would prove to be significant in understanding why certain stopes achieve greater levels of performance.

In relation to mining method performance, the influence of stope height on morphological complexity was studied. The parameter of stope height was used for convenience in attempting to prove whether complexity could be used to aid in the optimum design of a mining method. Utilising selected sections from the Manitoba Division orebodies it was found that complexity did increase with increased stope height. Analysis indicates that a mine should be able to determine a minimum acceptable performance once complexity has been characterised. Based on this limit the orebody model could be varied based on an anticipated range of complexity (based on historical or preliminary data). The mine design and method could be applied on to this model, varying the stope parameters according to complexity, to derive the optimum stope design and mining method through a form of simulation.

This thesis addresses the basic issue of how orebody complexity can be quantified. Further research is required to determine appropriate techniques to quantify the other elements of orebody complexity (geotechnical, grade distribution and ore mineralogy) and to find a means of bringing these elements together into one overall complexity index. The thesis has also addressed the relationship between morphological complexity and mining method performance, and initial results appear to be encouraging.

Finally, this thesis has demonstrated through actual case studies that geological control is required in order to achieve acceptable mining method performance. Geological control is considered to be a critical component in developing the new advanced mining technology which will be the foundation for future mine automation.

REFERENCES AND BIBLIOGRAPHY

Anon. 1993. Shaft Sinking at Louvicort. ICI Explosives Publication.

Annels, A.E. 1991. Mineral Deposit Evaluation - A practical approach. Chapman and Hall, London, 1st Edition. pp 43-47.

Ashcroft, J.W. 1991. Dilution: A Total Quality Improvement Opportunity. 93 rd CIM-AGM, Vancouver.

AutoCad™, 1990. Release 11. Autodesk Inc., publication AC11RM.

Baiden, G. R. 1995A study of underground mine automation. Unpublished Ph.D. Thesis, McGill University.

Bleeker, W. 1990. Evolution of the Thompson Nickel Belt and its nickel deposits, Manitoba, Canada. Unpublished Ph.D. Thesis, University of New Brunswick. pp. 16-20

Boyd, J. .M. 1988. Gravity and Structurally Controlled Failures, Canadian Mining and Industrial Equipment Exhibition, Laurentian University, Sudbury, Ontario, June 1,2,3, 1988.

Braun, D V. 1991. Ore interpretation Accuracy and its relationship to dilution at Inco's Thompson Mine. Prepared for publication at the 93rd CIM-AGM, Vancouver.

Carras, S. N. 1987. Ore reserve estimation methods and their relationship to recoverable reserves: Management and Economics of Mining Operations (Symposium Proceedings, Western Australian School of Mines, Kalgoorlie, October). pp 57-67.

Catalina, J.C., Artieda, J., Garcia, A. E., Ortea, J. J., Devy, K. M., Manana, R., 1993. Recent development on the use of computer vision as a face mapping tool. Mine. Mech. and Automation. (Eds) Almgren, Kumar and Vagenas, Balkema. pp 555.

Francis, H L. 1995. Errors in Ore Reserve Evaluation and a Reliability Rating System. Unpublished B.Sc. Thesis, University of Wales College of Cardiff.

Francis, H. L., Scoble, M. J., Paventi, M., Corkal, J. T. 1997. Simulating the Influence of Orebody Complexity on Underground Mining Performance. 99th CIM-AGM, Vancouver.

Goddard , G. J., Kelly, B. 1995. Applied Technology; A Cornerstone of the Future. Annual APEGN/CIM Meeting and Technical Conference, October 25-28, Newfoundland.

Gormley. 1987. Working with geological complexity at Quintette Coal Limited's Mesa Open Pit. 89th AGM-CIM, Toronto. CIM Bulletin. Sep. pp 57-70

Guilbert, J. M., & Parks, C. F. B. 1986. The geology of ore deposits. W. H. Freeman, New york.

Hartley, D. 1980. Development of Remote Monitoring and Control for Mining Systems. The Mining Engineer. pp 89

Jacob, D., Gendron, A. 1994. The Borehole Laser - Controls Dilution in Real Time. Solutions - a Noranda Technology Centre Publication.

Knights, P. F., Scoble, M. J. 1995. Integrated Mining Information and Control Systems; Towards the Digital Mine. AGM-SME, March 6-9, Colorado.

Knights, P. F. 1995. Automated Ore Tonnage Tracking Using RFID Systems. AGM-SME, March 6-9, Colorado.

Knissel, W., Jurgen, H., Fahlbusch, M. 1995. Significance of Selective Mining Exploitation for economical and environmentally beneficial underground ore mining. Mineral Resources Engineering. Vol. 5, No. 2. pp 165-174.

Langbridge, 1992.

Ledvina, C.T. 1986. geological Mapping can boost productivity, safety underground. Coal Age. Vol. 91, Apr. pp 54-61.

Lizotte, Y., Scoble, M. J. 1994. Studies on the effect of Rock Structure on Fragmentation. 95th Can. Inst. Min. Metall. Annual General Meeting, Calgary.

Maerz, N. H., Franklin, J.A., Bennett, C.P. 1990. Joint roughness measurements using shadow profilometry. Inst. J. Rock. Mech. and Min. Sciences and Geomechanics. Vol. 27. n. 5, Oct. pp 329-343.

Martin, C.D., 1990. Characterising InSitu Stress Domains at the AECL Underground Research Laboratory. Can. Geotech. J. Vol. 28, pp. 503-516.

McCullouch, B. G., Grunn, P. 1993. Construction Field Data Acquisition with Pen-Based Computers. J. Const. Eng. Mang. Vol. 119, No. 2.

Momayez, M., Hara, A., Hassani, F. P. 1995. application of GPR in Canadian Mines. CIM Bulletin. Vol. 89, June. pp 107-110

Morrison, D. M. 1995. Deep hard Rock Mining - The Future. 95th Can. AGM-CIM, Vancouver.

Paventi, M. 1990. Dilution in Underground Mining - A Review of Current and Prior Research. Unpublished, McGill University.

Paventi, M., Scoble, M. J., Szymanski, J. 1992. Peridotites: Geomechancial Characteristics and Ground Control. Proc. Rock Mechanics and Strata Control Session, 94th Can. Inst. Min. Metall. Annual General Meeting, Montreal, pp. 100-111.

Paventi, M. 1995. Rock Mass Characteristics and Damage at Birchtree Mine. A Ph. D. thesis submitted to the Faculty of Graduate Studies and Research in the Department of Mining Engineering, McGill University Montreal

Pearson, W.N and Watts, G.D. 1984. The portable Microcomputer in mineral exploration: bridging the gap between field and office. Comp. Apps in Min. Exp. (Eds) Sheahan, P. pp 36-37.

Peck, J., Hendricks, C., Scoble, M.J. 1989. Performance monitoring of electric mining shovels. Trans. IMM. Section A-Min. Ind. Vol. 98 Sep-Dec 1989 p. A151-A159

Platford, R. E., Mundy, D. C., Bonyai, C. G. 1991. Dilution Control at Inco's Thompson Mine, Manitoba Division.

Potvin, Y., Hudyma, M. R., Miller, H. D. S. 1988. Volume 1- Final Report: Integrate Mine Design project, NSERC project # CRD-8612, pp. 105-161.

Puhakka, R. 1990. Geology Waste Rock Dilution, The Finish Association of Mining and Metallurgical Engineers, No. 94.

Ruttan, G. D. 1968. ore Estimation and Grade Control at Sherritt Golden's Lynn Lake Operation: Ore Reserve Estimation and Grade Control. CIM Special Publication. Vol. 9, Sept 25-27, pp. 139-143.

Sabsabi, M. 1996. Report on Laser Induced Plasma Spectroscopy. Unpublished.

Scoble, M. J. Moss, A. 1994. Dilution in underground metal mining: implications for grade control and production management. Mineral Resources Evaluation II: Methods and Case Histories, ed. Whateley, M. K. G., Harvey, P. K. The Geological Society, London.

Scott, 1997. Quintette - Post 1997. 99th Can. AGM-CIM, Vancouver.

Sommer, G. 1992. A Contemplative Stance on the Automation of the Mining, Mineral and Metal processing Industry (MMM). An IFAC (International Federation of Automatic Control) Report. Automatica. Vol. 28, No. 6, pp 1273-1278.

Sorenson, *et al.* 1997. Presentation made at Inco Limited, Manitoba Divison, Mines Reasearch.

Wanstedt, S., Sundin, N. O. 1991. Geophysical borehole logging applied to mine planning in Swedish Mines. Mine. Mech and Aut. (Eds) Almgren, Kumar and Vagens. Balkema. pp 215.

Whiteway, P., *et al.* 1995. A Geologists Mine - Louvicort. Supplement to Canadian Mining Journal. pp 12-44.

Whiteway, P. 1993. Just in Time Mining. Can. Min. J. Aug.

Pers. Comm.

Cochrane, L. 1997. Inco Limited, Ontario Division, Mines Technical Services.
Hinton, E. 1997. Inco Limited, Ontario Division, Mines Research.
Owens, D. 1997. Inco Limited, Manitoba Division, Mines Technical Services.
Pen Systems Inc. 1996. Pen Systems, Canada.
Preston, C. 1997. Dyno Nobel Limited, Ontario.
Scoble, M. J. 1997. McGill University, Montreal.
Sorenson, G. 1997. Inco Limited, Manitoba Division, Mines Research.
Thompson, B. 1997. Inco Limited, Ontario Division, Mines Technical Services.

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Graphs and Charts In Appendicies I-III

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APPENDIX I

Tabulated Data for Optimum Stope Height versus Complexity

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht1	431	120	1447	268	2095	383	3123	492
	956	159	1686	240	2658	346	2211	431
	535	129	1482	241	2073	610	12274	1520
	1072	139	513	218	10744	1173		
	813	138	6727	1063				
	626	129	5333	868				
	360	120						
	175	109						
	1516	399						
	5349	713						
	5323	788						
	142	87						
stht2	181	132	326	243	472	347	598	455
	192	113	300	212	712	325	1458	436
	138	109	482	222	1298	360	1815	469
	145	112	763	232	1687	366	2073	427
	198	110	981	244	1501	322	4984	821
	287	116	1049	238	1329	332	8824	1082
	611	128	820	222	8685	922	741	266
	261	125	1156	227	4925	651		
	339	135	856	223	741	266		
	554	149	4078	609				
	428	136	3793	86				
	524	120	1216	310				
	453	123	842	263				
	370	116						
	585	127						
	632	134						
	521	123						
	283	117						
	869	256						
	3121	418						
	4635	496						
	3755	503						
	928	156						
	359	181						
	578	206						
	214	84						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht3	243	112	470	215	667	322	1093	419
	130	115	540	212	926	321	926	424
	197	112	498	224	369	337	1336	441
	464	119	276	222	1095	331	2136	431
	223	115	452	229	1208	324	1374	453
	248	118	682	224	1917	344	9150	1311
	197	114	666	222	1776	525	6479	71
	103	111	1471	231	7821	1106		
	174	124	1017	240	5594	610		
	375	114	352	225				
	275	118	3208	588				
	394	127	5934	843				
	167	114	4902	434				
	487	120	1639	306				
	501	124						
	822	137						
	626	138						
	437	122						
	166	106						
	228	126						
	1308	354						
	2043	383						
	2498	314						
	3218	641						
	2295	324						
	2495	271						
	960	227						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht4	839	207	954	242	919	333	1003	427
	318	88	179	240	3811	611	8440	1064
	19	99	3696	487	5978	829	1849	487
	72	108	4962	750	783	299	1544	411
	54	35	1508	295	1054	308	1788	441
	1950	329	487	207	1250	393	2522	737
	1573	217	606	208	1730	413	6068	1009
	3414	469	883	221	2704	651	10328	870
	666	368	601	227	5035	767		
	1219	183	1396	237	9835	872		
	225	168	304	305				
	293	114	1469	442				
	207	107	1615	547				
	268	113	4252	515				
	355	112	8023	649				
	338	114	1681	291				
	395	123						
	275	121						
	329	114						
	541	131						
	908	138						
	387	119						
	338	199						
	441	216						
	1011	248						
	1151	265						
	650	294						
	1492	302						
	2780	311						
	3932	390						
	3677	442						
	1639	292						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht5	4352	292	8668	408	1078	530	11505	622
	4386	287	2941	382	1768	386	1592	466
	2211	290	1111	285	2660	398	4936	480
	769	141	1133	229	4448	605	4643	958
	660	150	2276	412	4308	864	3077	688
	330	144	2024	421	2367	424	3134	799
	477	127	2625	622	1795	664	904	436
	528	130	2330	323	1722	742		
	895	199	1550	288	502	336		
	1092	250	1033	397	38	105		
	1213	298	1245	597				
	885	163	1093	355				
	1562	317	632	244				
	1083	340	131	214				
	1323	208						
	881	183						
	807	152						
	699	167						
	654	243						
	243	202						
	598	235						
	712	257						
	742	235						
	397	132						
	232	126						
	219	118						
	214	120						
	38	105						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht6	7007	393	[illegible]	505	18496	645	22130	900
	6469	388	[illegible]	619	3745	690	819	852
	5050	365	[illegible]	528	526	647	2091	550
	2611	357	[illegible]	433	2089	44	3856	770
	846	187	[illegible]	327	1133	413	4791	1154
	344	208	693	255	3229	827	2915	681
	87	220	913	304	3736	1137	503	136
	116	222	2639	510	2683	559		
	124	211	[illegible]	802	933	255		
	459	205	2500	718				
	1148	209	2354	441				
	478	129	[illegible]	245				
	175	134	[illegible]	138				
	83	105						
	926	200						
	1281	228						
	1386	349						
	907	381						
	867	456						
	1311	409						
	1580	371						
	2060	315						
	194	113						
	276	121						
	501	142						
	513	136						

Stope height	50 ft				150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht7	238	223		228	2381	701	4526	756
	430	24[illegible]		224	2509	528	1311	458
	2026	284		339	1646	601	17013	1477
	1653	31[illegible]		257	15780	1203	10122	1776
	673	1[illegible]		366	7959	1307	5412	798
	266	176		360	6815	1079	1005	453
	166	105		989	1631	557	644	605
	236	112		923	732	338		
	687	144		822	518	287		
	2426	77[illegible]		649	1015	313		
	4783	803		457				
	6024	794		309				
	4886	6[illegible]		219				
	2140	396		487				
	1501	409		247				
	1859	5[illegible]						
	2316	427						
	1798	370						
	883	342						
	379	199						
	408	120						
	243	199						
	162	[illegible]						
	[illegible]	[illegible]						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht8	1592	396	[illegible]	270	5918	1791	6607	958
	1905	369	[illegible]	466	1161	391	1541	525
	2483	254	[illegible]	387	2472	362	3112	787
	662	196	[illegible]	239	2371	456	5562	1329
	466	127	[illegible]	297	2977	816	4558	669
	161	121	[illegible]	278	6663	816	2101	561
	151	119	[illegible]	354	1594	482	1922	455
	621	20[illegible]	[illegible]	544	1499	363		
	1045	366	[illegible]	169	1573	360		
	1140	165	[illegible]	667	372	117		
	848	171	[illegible]	431				
	476	208	[illegible]	288				
	666	343	[illegible]	317				
	437	253	[illegible]	252				
	1878	327	[illegible]	474				
	2472	577						
	2706	379						
	1214	179						
	340	180						
	529	130						
	727	228						
	645	138						
	534	138						
	449	128						
	495	134						
	496	133						
	527	136						
	302	116						

Stope height	50 ft		[illegible] ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht13	824	208		428	3123	594	5357	1022
	1376	318		646	5662	757	4507	676
	896	204		465	1328	334	2013	431
	2225	505		230	1471	324	1631	519
	3039	359		228	1026	394	5339	556
	702	208		225	3533	410	2006	523
	299	115		252	3163	477	1074	437
	504	12[illegible]		276	1579	322		
	316	124		336	533	329		
	500	120		320	327	106		
	593	120		221				
	520	12[illegible]		225				
	427	146		220				
	112	112		223				
	324	156						
	664	151						
	562	182						
	208[illegible]	20[illegible]						
	18[illegible]	25[illegible]						
	865	203						
	433	122						
	389	12[illegible]						
	5[illegible]	12[illegible]						
	629	132						
	295	114						
	176	11[illegible]						
	203	118						
	327	106						

Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht14	1354	381	5460	759	9194	1064	11039	1275
	3864	518	4824	777	3608	1028	4892	1564
	3370	543	1975	771	3556	1120	3656	854
	1584	360	2571	845	2895	518	2676	466
	1144	503	1724	462	2139	363	2799	257
	901	275	1552	330	3526	339		
	1153	387	1274	253				
	1415	508	1164	237				
	1171	311	2490	256				
	1615	483						
	705	131						
	826	168						
	463	125						
	653	128						
	601	108						
	1104	145						
	1482	157						
stht15	279	205	2130	838	7274	1268	7910	1433
	2551	771	1116	707	2384	608	2064	556
	3164	498	1124	348	914	317	1924	449
	885	289	1128	216	1382	340	1065	489
	731	135	1110	213	876	350	3459	472
	689	271	963	242	1872	428	1940	429
	204	114	1106	242	1942	347	1718	317
	282	113	1103	287	1211	320		
	587	117	1104	281	1699	322		
	408	119	1103	253				
	377	129	1107	223				
	560	133	1103	227				
	390	145	1170	221				
	141	112	1113	121				
	167	111						
	205	160						
	310	118						
	1231	194						
	1015	139						
	438	129						
	281	113						
	268	105						
	411	122						
	414	120						
	562	128						
	484	124						
	448	121						

Stope height	[illegible] ft		[illegible] ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht16	[illegible]	21[illegible]	[illegible]	[illegible]41	4484	1152	6063	1574
	18[illegible]	56[illegible]	[illegible]	950	6159	903	6950	844
	21[illegible]	45[illegible]	[illegible]	533	4339	492	2626	707
	16[illegible]	47[illegible]	[illegible]	300	1471	432	2173	612
	1554	250	[illegible]	389	1722	378	2077	422
	2277	298	[illegible]	324	1529	437		
	9[illegible]	180	[illegible]	232	804	244		
	2026	209	[illegible]	342				
	1029	249	[illegible]	214				
	3[illegible]	160		[illegible]20				
	[illegible]	18[illegible]						
	49[illegible]	15[illegible]						
	5[illegible]	12[illegible]						
	5[illegible]	13[illegible]						
	43[illegible]	169						
	438	209						
	7[illegible]	12[illegible]						
	2[illegible]	12[illegible]						
	43[illegible]	123						
	19[illegible]	11[illegible]						

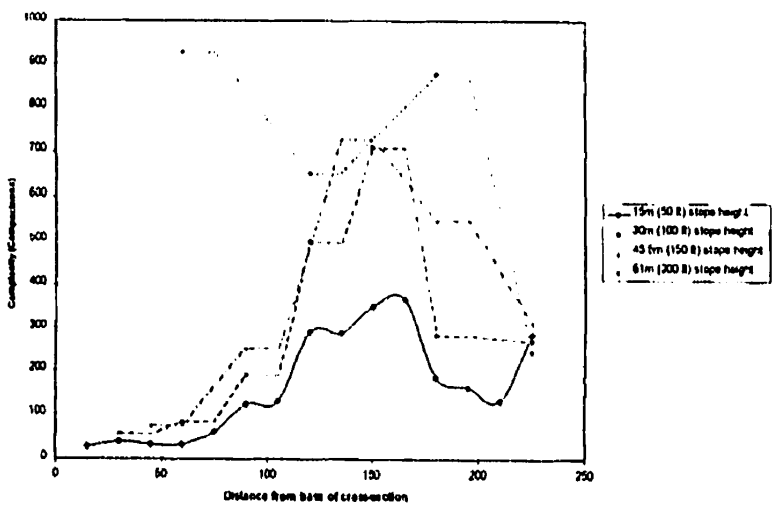
Stope height	50 ft		100 ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht17	328	115	[illegible]	224	1052	327	1473	432
	404	131	[illegible]	224	1414	492	3060	796
	299	120	[illegible]	383	2143	593	915	479
	265	118	[illegible]	481	774	352	2129	458
	424	168	[illegible]	236	1157	338	3490	593
	815	245	[illegible]	240	1674	422	1473	373
	1093	292	[illegible]	159	4468	670		
	543	128	[illegible]	282				
	321	144	[illegible]	255				
	214	111	[illegible]	294				
	166	121	[illegible]	380				
	299	131						
	145	111						
	78	55						
	868	167						
	732	205						
	538	125						
	312	125						
	1173	267						
	1529	235						
	1387	371						
stht18	113	109	[illegible]	215	407	330	407	429
	98	109	[illegible]	216	427	358	2476	523
	157	118	[illegible]	259	2784	406	3274	548
	155	108	[illegible]	268	1233	347	2612	640
	393	121	[illegible]	303	1525	417	9873	526
	310	152	[illegible]	275	6092	491		
	770	162	[illegible]	296	2106	543		
	910	149	[illegible]	362				
	974	170	[illegible]	326				
	645	131	[illegible]	534				
	564	162						
	825	148						
	600	130						
	449	120						
	397	134						
	10007	244						
	2245	200						
	2756	244						
	1034	260						
	804	250						

Stope height	50 ft		[illegible] ft		150 ft		200 ft	
	Area	Perim	Area	Perim	Area	Perim	Area	Perim
stht19	157	110	[illegible]	222	559	334	976	442
	167	117	[illegible]	227	738	310	1311	420
	175	118	[illegible]	207	1646	463	4730	618
	156	111	[illegible]	218	3322	446	2759	568
	357	116	[illegible]	336	2024	407	5161	654
	222	109	[illegible]	283	4346	427		
	171	108	[illegible]	288	2218	364		
	314	129	[illegible]	343				
	1100	257	[illegible]	371				
	1941	182	[illegible]	400				
	932	185						
	660	162						
	802	178						
	502	144						
	562	164						
	531	193						
	970	247						
	1848	197						
	1142	236						
	758	198						
stht20	757	127	[illegible]	247	2860	398	4543	590
	684	143	[illegible]	376	4266	392	3914	687
	1307	187	[illegible]	276	4344	521	7093	539
	1650	280	[illegible]	423	4828	419	2588	494
	1504	164	[illegible]	326	1921	382	1870	509
	659	141	[illegible]	275	1448	355		
	243	131	[illegible]	262	505	295		
	1497	314	[illegible]	272				
	2611	211	[illegible]	236				
	2115	192	[illegible]	296				
	1450	169						
	1119	161						
	935	141						
	559	174						
	589	154						
	178	121						
	413	126						
	462	134						
	360	139						
	233	110						

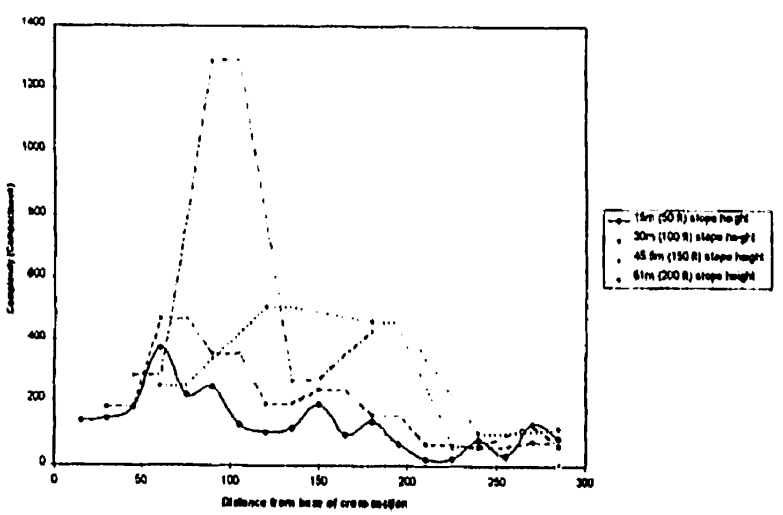
APPENDIX II

Complexity versus distance from base of cross sections for various stope heights

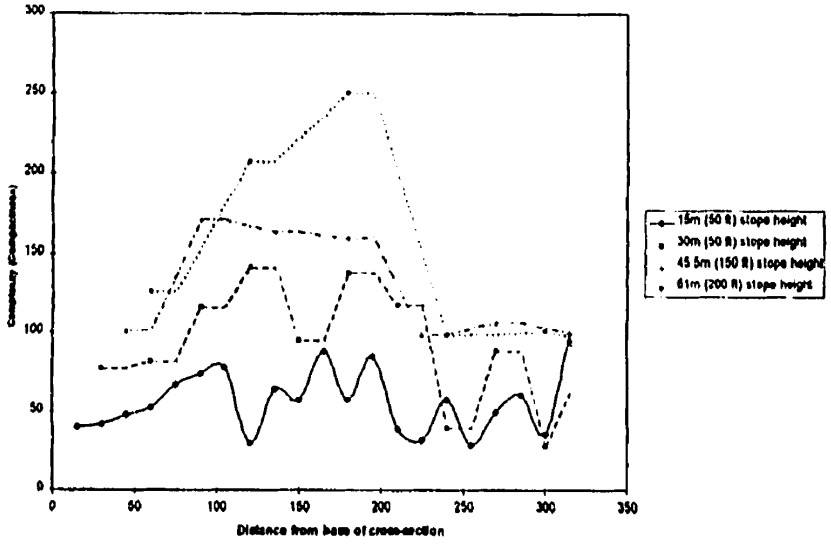
Thompson (T3) 1D Orebody - s35150 (sth121)



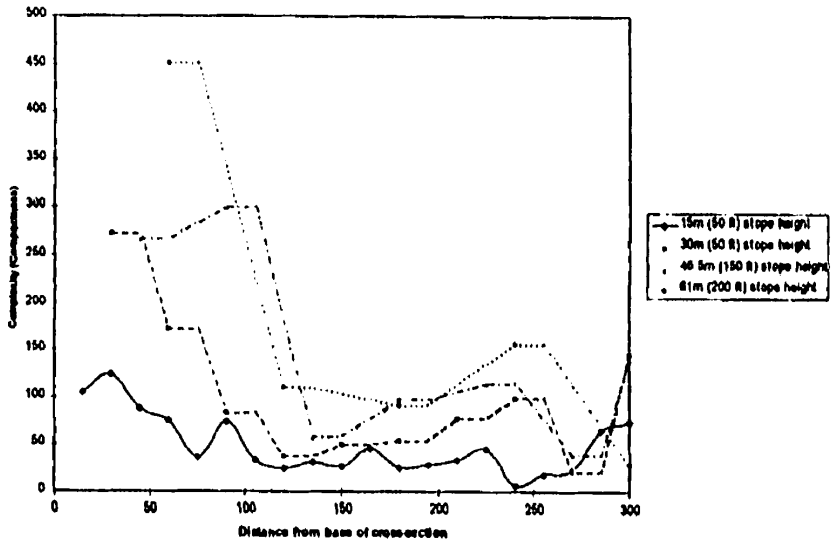
Thompson (T3) 1D Orebody - s35250



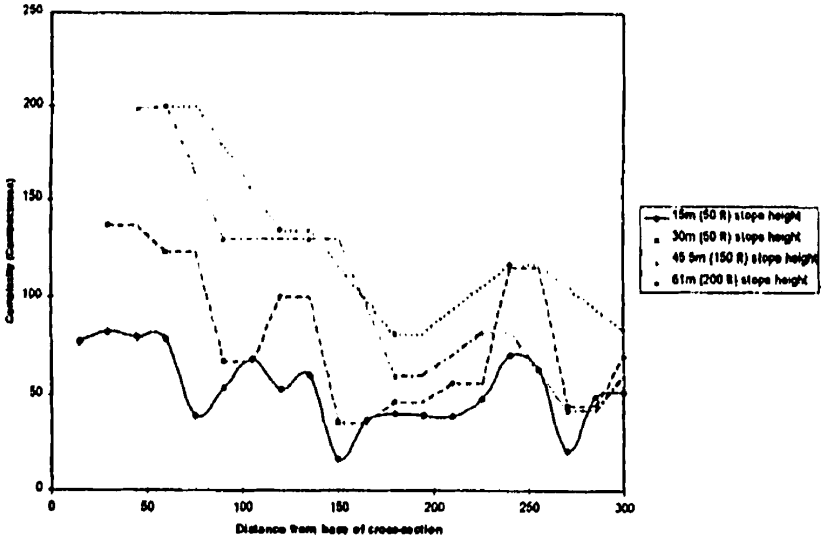
Birchtree 83 Orebody - s9350 (sfht17)



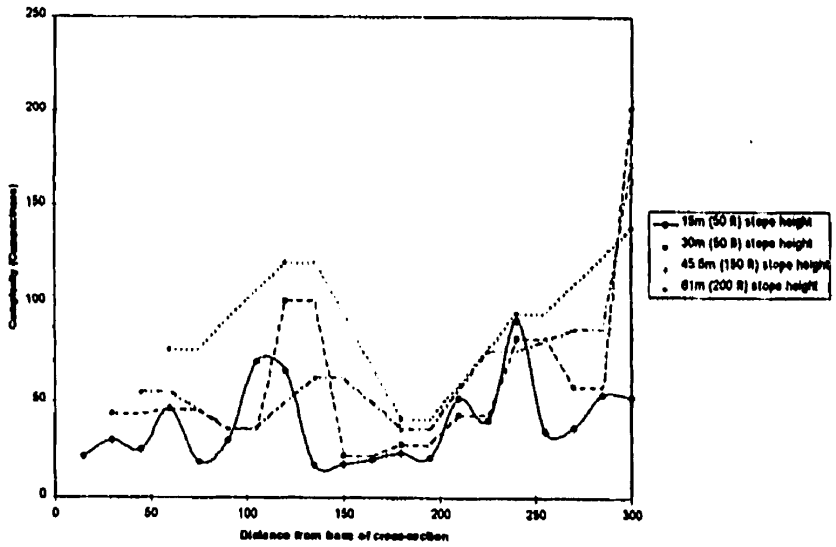
Birchtree 83 Orebody - s9500 (sfht18)



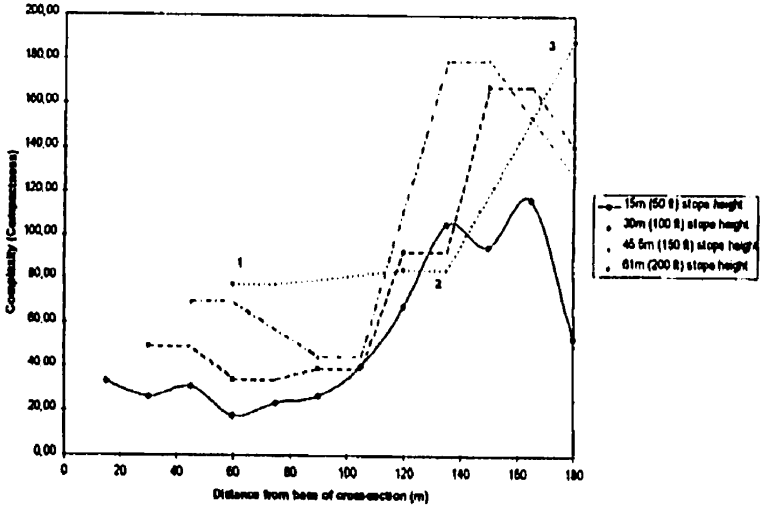
Birchtree 83 Orebody - s9600 (sfht19)



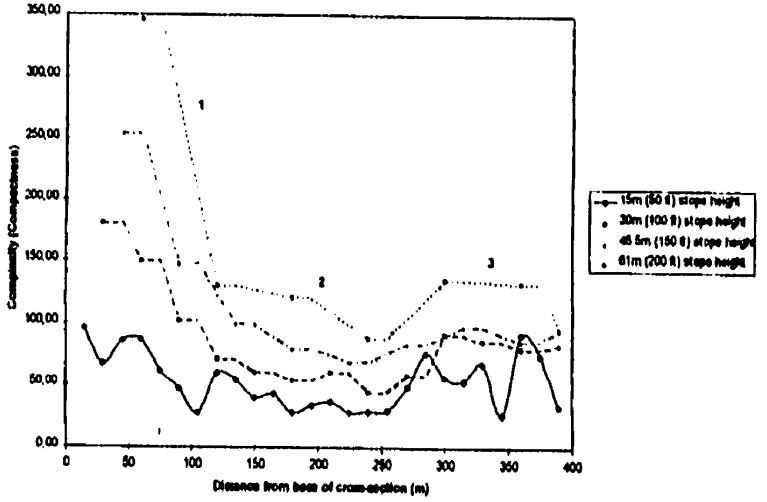
Birchtree 83 Orebody - s9650 (sfht20)



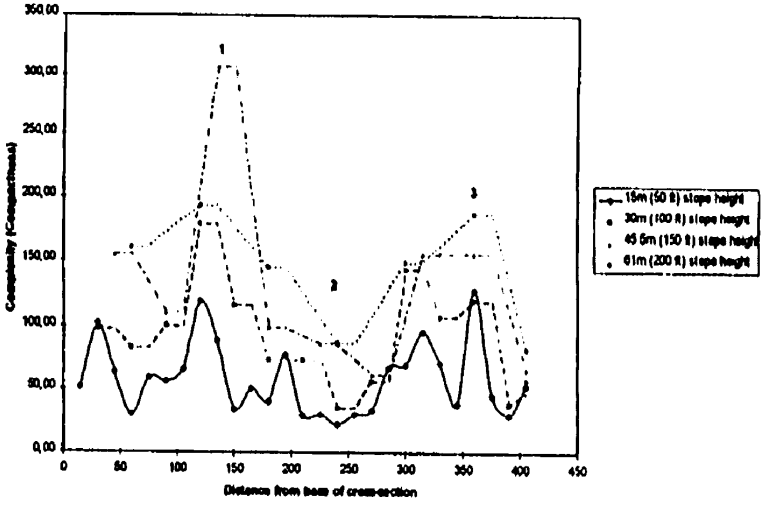
Thompson (T1) 3SHEAR Orebody - s845 (sht1)



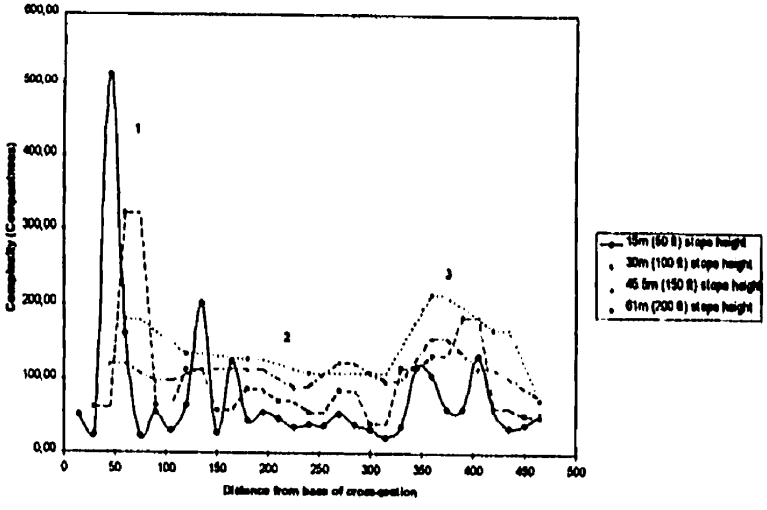
Thompson (T1) 3SHEAR Orebody - s860 (sht2)

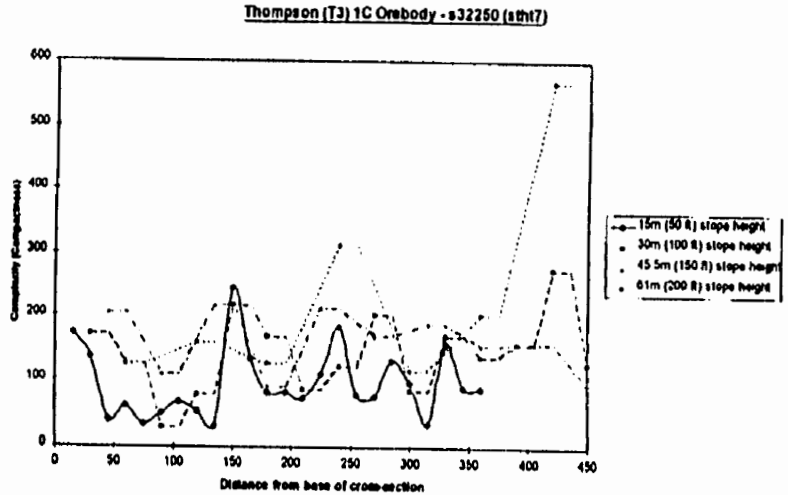


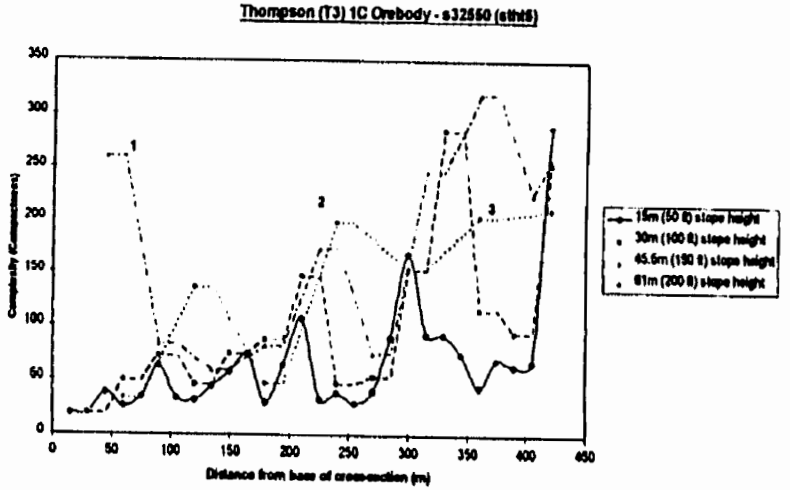
Thompson (T1) 3SHEAR Orebody - s875 (sht3)

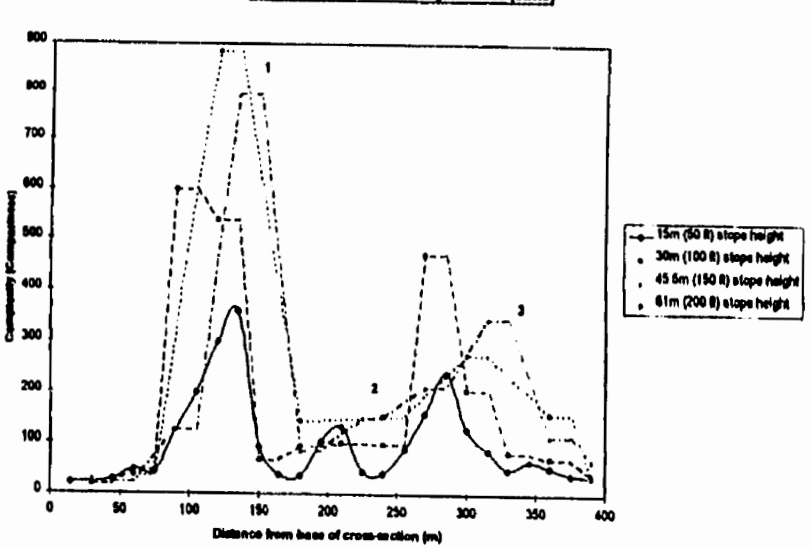


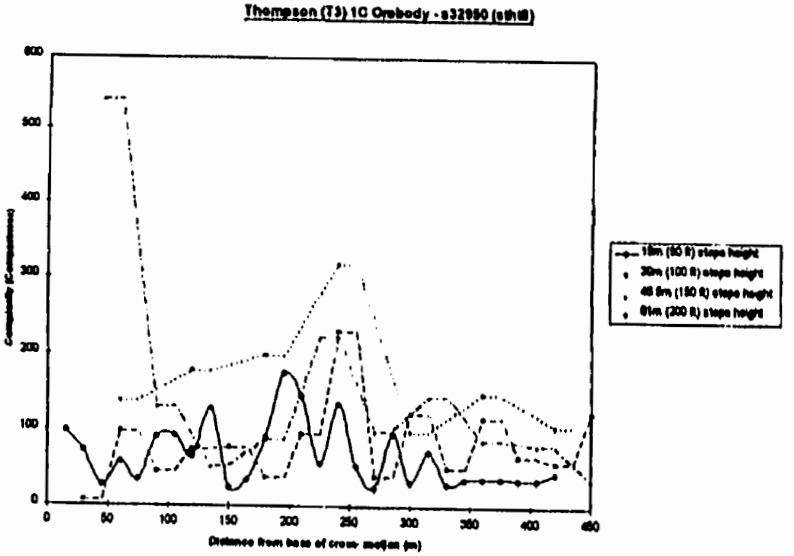
Thompson (T1) 3SHEAR Orebody - s900 (sht4)




Thompson (T3) 1C Orebody - s32250 (stht7)
Distance from base of cross-section
15m (50 ft) stope height
30m (100 ft) stope height
45.5m (150 ft) stope height
61m (200 ft) stope height

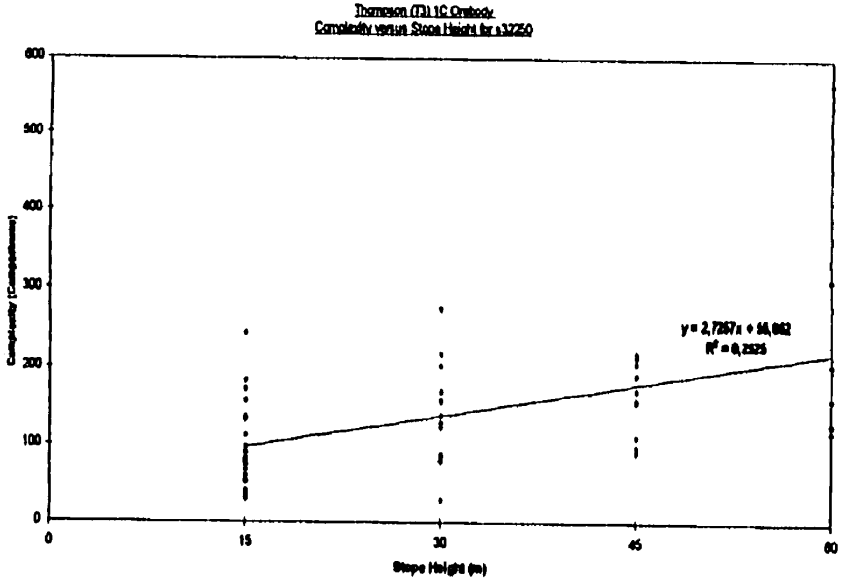

Thompson (T3) 1C Orebody - s32550 (stht6)
Distance from base of cross-section (m)
15m (50 ft) stope height
30m (100 ft) stope height
45.5m (150 ft) stope height
61m (200 ft) stope height

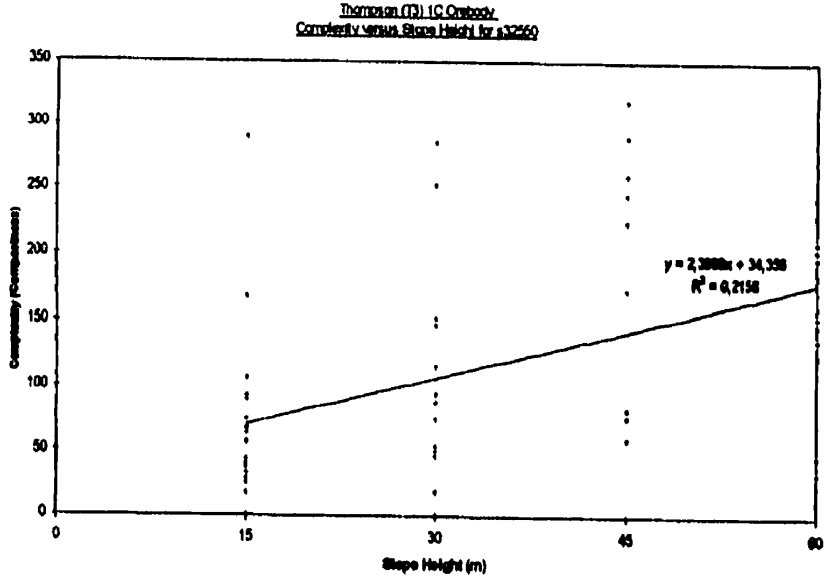

Thompson (T3) 1C Orebody - s32650 (stht6)
Distance from base of cross-section (m)
15m (50 ft) stope height
30m (100 ft) stope height
45.5m (150 ft) stope height
61m (200 ft) stope height

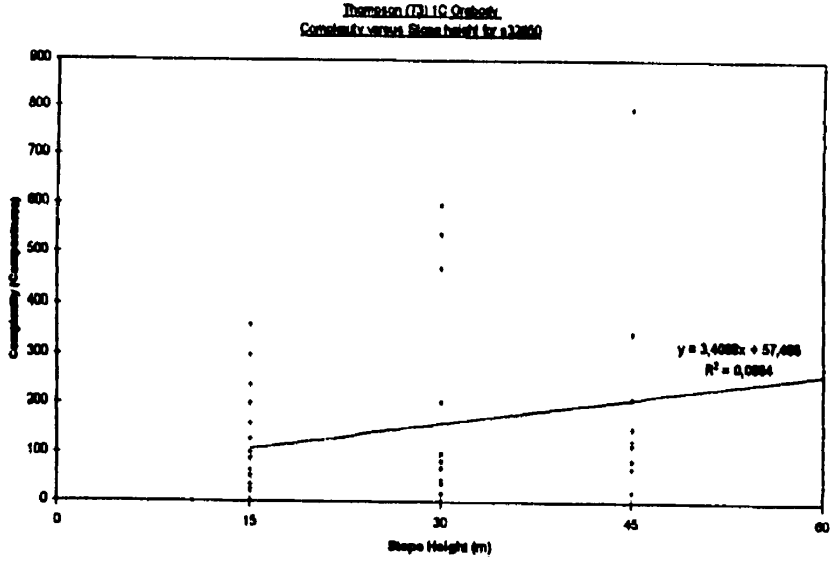

Thompson (T3) 1C Orebody - s32950 (stht6)
15m (50 ft) stope height
30m (100 ft) stope height
45.5m (150 ft) stope height
61m (200 ft) stope height

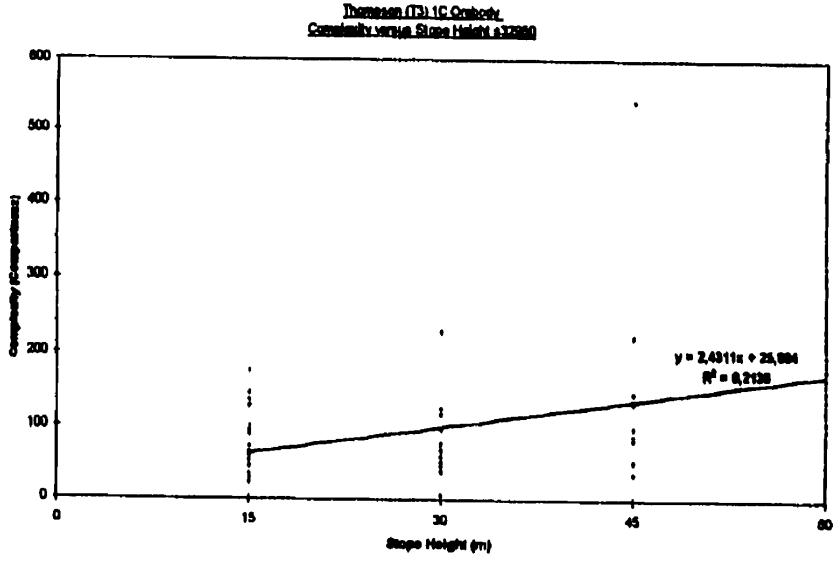
APPENDIX III

Trendlines for Complexity versus Stope Height

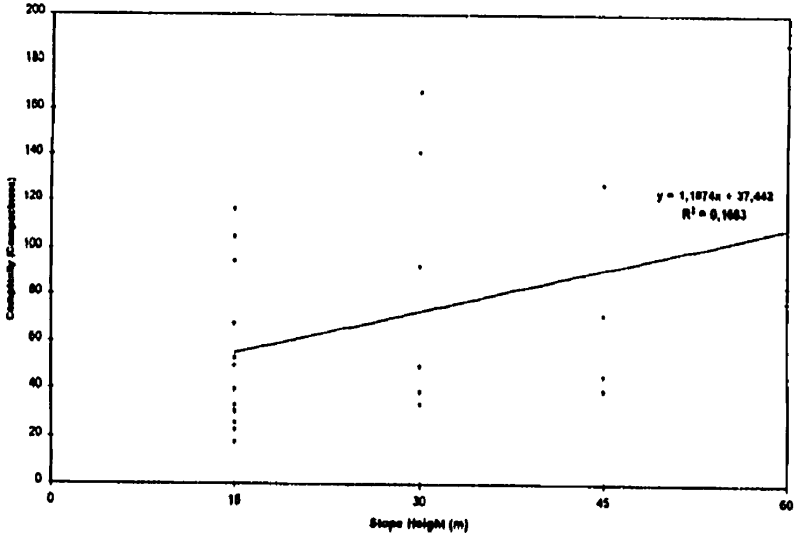

Thompson (T3) 1C Orebody
Complexity versus Slope Height for s32250
Complexity (Compactness)
Slope Height (m)
y = 2,7257x + 56,982
R² = 0,2525


Thompson (T3) 1C Orebody
Complexity versus Slope Height for s32550
Complexity (Compactness)
Slope Height (m)
y = 2,3998x + 34,358
R² = 0,2158

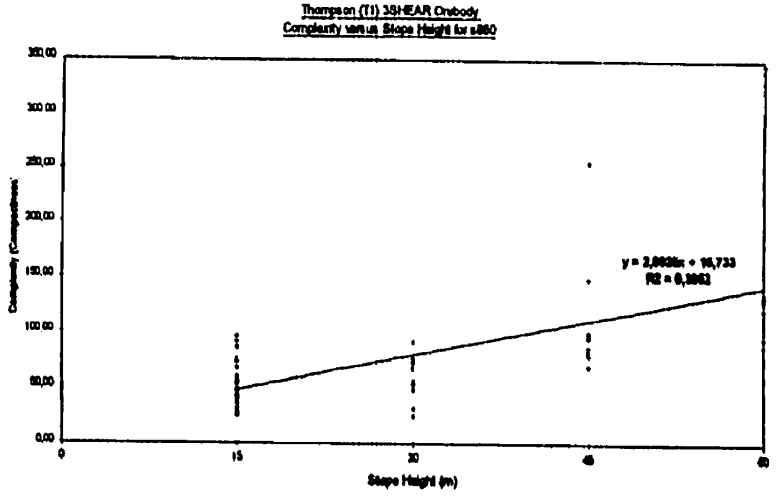

Thompson (T3) 1C Orebody
Complexity versus Slope Height for s32850
Complexity (Compactness)
Slope Height (m)
y = 3,4088x + 57,488
R² = 0,0884


Thompson (T3) 1C Orebody
Complexity versus Slope Height s32950
Complexity (Compactness)
Slope Height (m)
y = 2,4311x + 25,994
R² = 0,2139

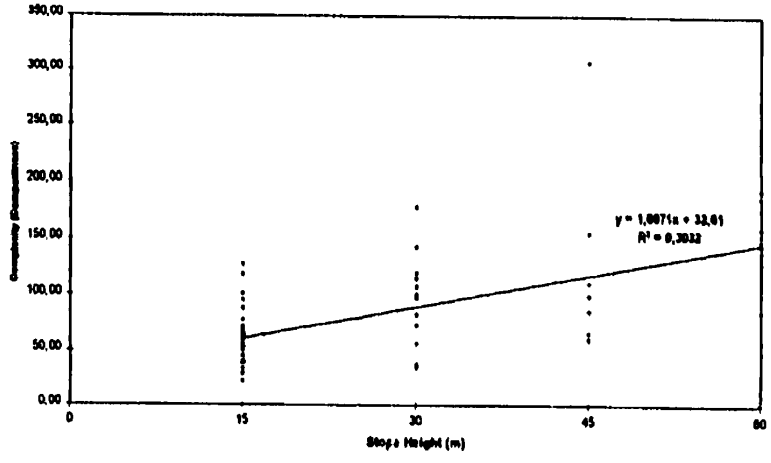
Thompson (T1) 3SHEAR Orebody
Complexity versus Slope Height for s845



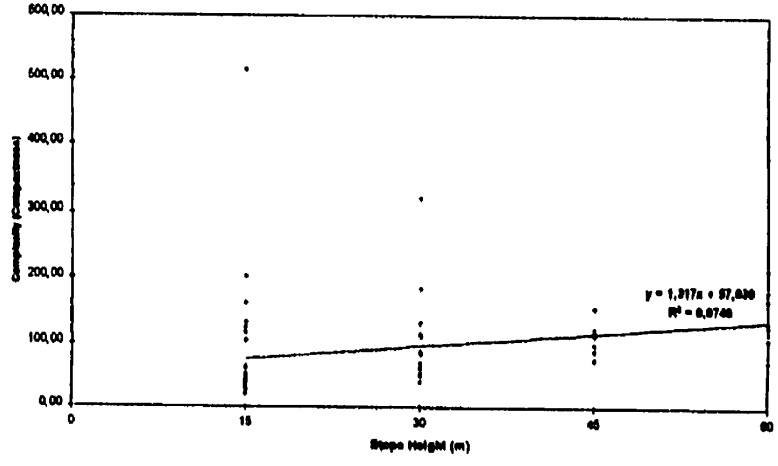
Thompson (T1) 3SHEAR Orebody
Complexity versus Slope Height for s860

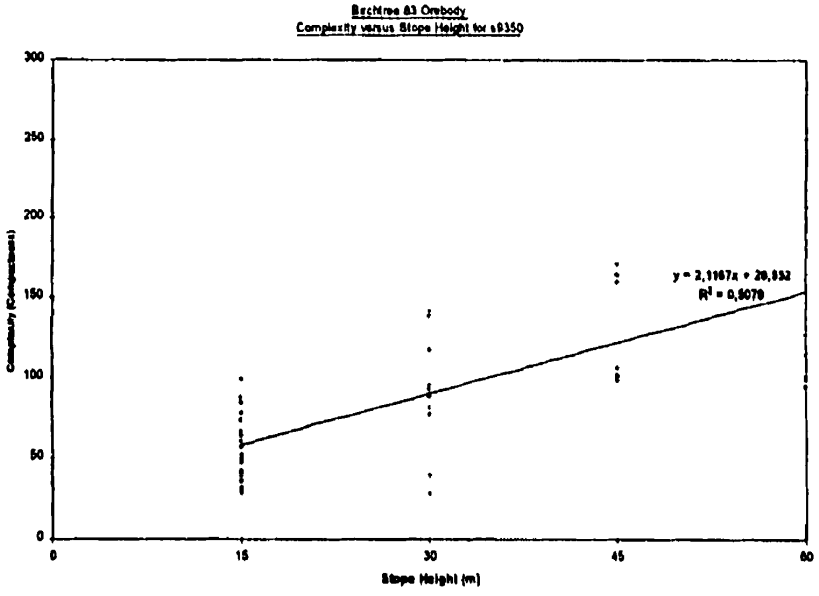


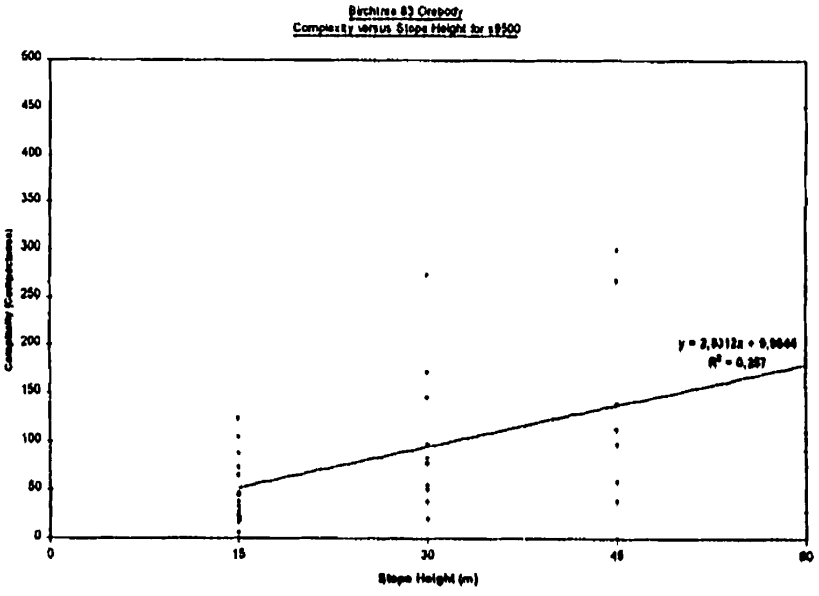
Thompson (T1) 3SHEAR Orebody
Complexity versus Slope Height for s876

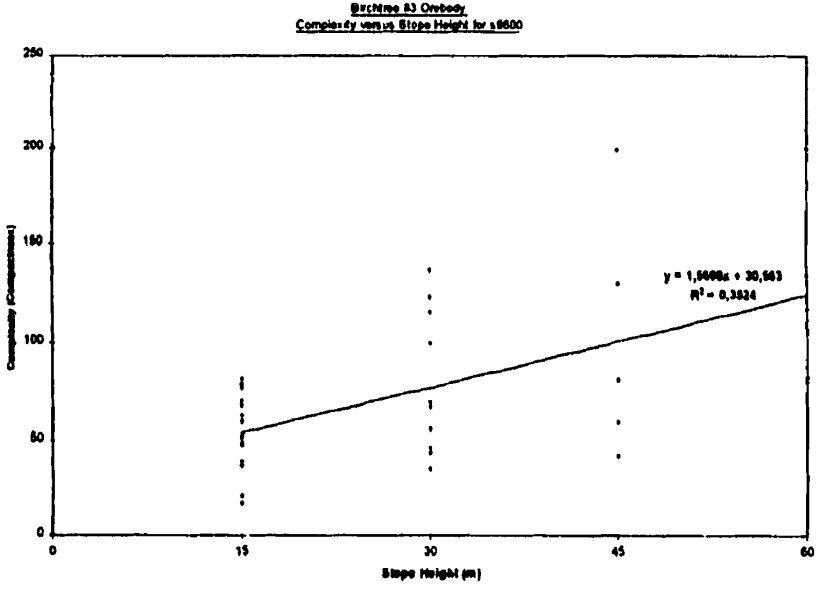


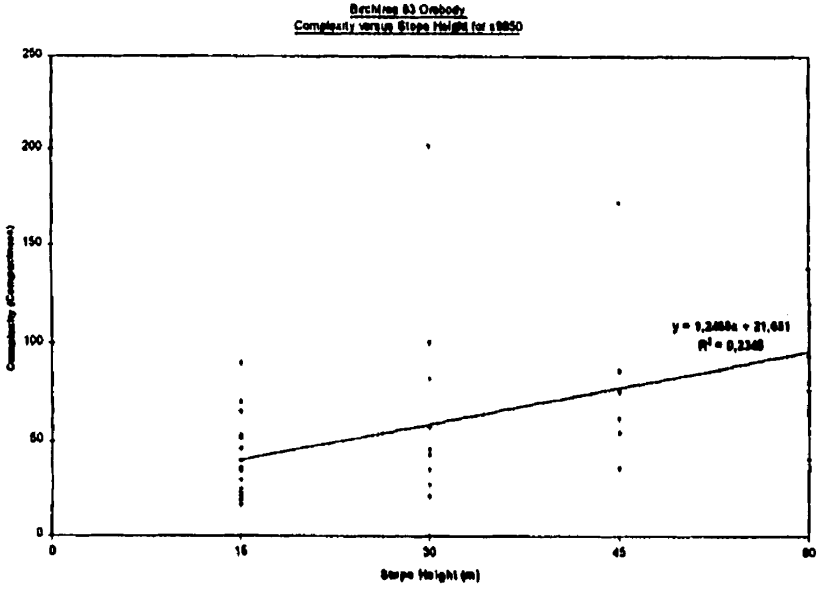
Thompson (T1) 3SHEAR Orebody
Complexity versus Slope Height for s900

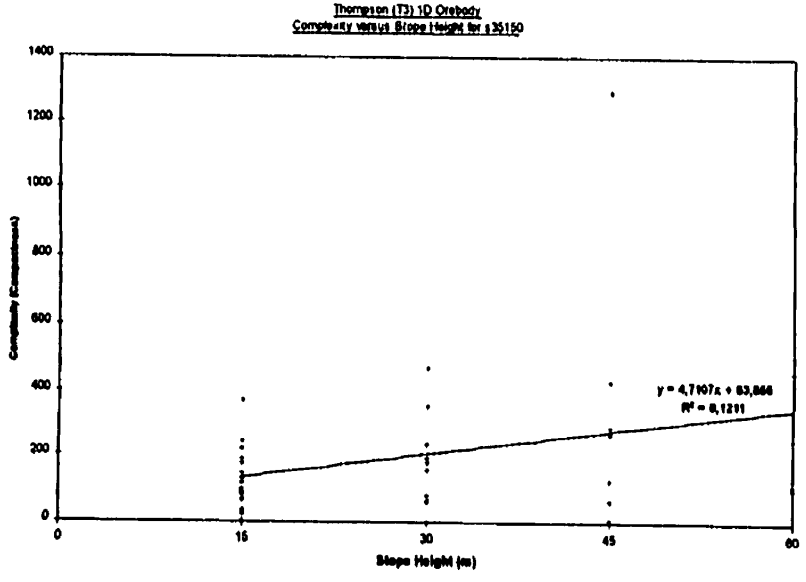


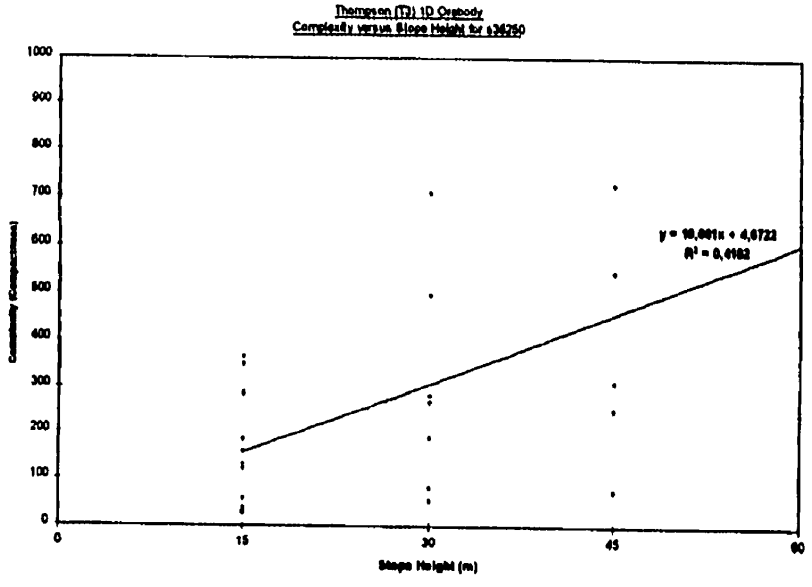

Birchtree 83 Orebody
Complexity versus Slope Height for s9350
Complexity (Compactness)
Slope Height (m)
y = 2,1167x + 29,832
R² = 0,5079


Birchtree 83 Orebody
Complexity versus Slope Height for s9500
Complexity (Compactness)
Slope Height (m)
y = 2,8312x + 9,9644
R² = 0,257


Birchtree 83 Orebody
Complexity versus Slope Height for s9600
Complexity (Compactness)
Slope Height (m)


Birchtree 83 Orebody
Complexity versus Slope Height for s9650
Complexity (Compactness)
Slope Height (m)


Thompson (T3) 1D Orebody
Complexity versus Slope Height for s35150
Complexity (Comparisons)
Slope Height (m)
y = 4,7197x + 83,866
R² = 0,1291
0
200
400
600
800
1000
1200
1400
0
15
30
45
60


Thompson (T3) 1D Orebody
Complexity versus Slope Height for s34750
Complexity (Comparisons)
Slope Height (m)
y = 10,691x + 4,6722
R² = 0,4182
0
100
200
300
400
500
600
700
800
900
1000
0
15
30
45
60